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GEIGER-MUELLER COUNTERS.

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(*Continued from May issue.*)

THE PROPERTIES OF A GOOD COUNTER.

In order to know whether we have a good counter and how to test it, or indeed in order to know what a good counter is, it is necessary first to outline the mode of action of a counter in operation. Once the discharge mechanism is clearly understood, it becomes possible to understand what the method of preparation of a good counter has accomplished. We are able to see also what limitations there are to the possibility of attaining the desired counter properties, and how a given counter can be employed to the best advantage. We shall list below the five most important features of counter behavior which are desirable to obtain, and then proceed to discuss them individually. These properties are:

1. High Efficiency. The counter should respond to every ray passing through it.
2. Large Pulses. The change in potential of the counter wire should be sufficiently large so that there are no complications in recording the potential changes.

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3. No Spurious Counts. The number of counter discharges which occur spontaneously without the passage of a ray through the counter should be a minimum.
4. Fast Pulses. The rate of change of potential of the wire should be large.
5. Small Lags. The time interval between the passage of a ray through the counter and the appearance of an appreciable change of potential of the wire should be as small as possible.

No counter can be made which possesses these five desirable characteristics to the highest degree. It is possible, however, to choose the best compromise among them for the particular purpose in mind.

The Discharge Mechanism.—When an ion pair is formed in the gas between the electrodes of a Geiger-Mueller counter, the electron will be accelerated toward the wire while the positive ion drifts toward the cylinder. When the electron comes close to the wire, it will attain sufficient energy so that it will excite the atoms of the gas, and when it has gained somewhat more energy, it will eject electrons from the gas molecules and ionize them. These ejected electrons will in turn gain energy and produce still others and we have the process taking place which is known as ionization by collision, a rather inappropriate term since *all* ionization occurs as the result of a "collision." Now a positive ion and an electron have very different mobilities. In a given electric field the electron will move more than a thousand times as fast as a positive ion. Hence we can neglect the motion of the ions, in the first approximation, when we are dealing with the motions of electrons. Thus, the single electron of the original ion pair has produced others which travel with it toward the wire leaving behind a stationary space charge of positive ions. Such a group of electrons is called an electron "avalanche" and consists of several hundred members. In the process of the creation of this group of electrons and their passage toward the counter wire a number of photons are also created which spread throughout the counter. Some of these photons are of short wavelength and will eject photoelectrons when they strike the cathode. These photoelectrons will produce new electron

avalanches at another point along the length of the counter. This process continues until a large number of electrons has been created as a result of the action of the single original one.[20] During this time, the number of positive ions has been correspondingly increased and they form around the wire a considerable space charge which is still relatively stationary. This positive space charge reduces the field near the wire, exactly as if the diameter of the positively charged wire had been increased, and stops eventually the creation of new avalanches. At this point the electrons have all reached the wire, no photons are present, and the active portion of the discharge process may be regarded as complete. The time taken for this process is very small, probably of the order of 10^{-7} to 10^{-8} seconds for a counter one centimeter in diameter. The multiplication and the creation of these electron avalanches and consequently the positive space charge which is left behind them, have all occurred *very* close to the wire, at distances less than the wire diameter. Thus, even though as many as 10^{9} or 10^{10} electrons have reached the wire, the electricity has not been moved very far, and consequently the potential of the wire is very little changed.

We have the apparently paradoxical situation, then, that the original ray has passed through the counter, produced an ion pair, the original pair has been multiplied to a great many others by the processes of a gas discharge, and this discharge has been extinguished before the potential of the counter wire has changed. This is all, of course, not exactly so, since the positive ions are not completely stationary and the electrons have not been formed exactly at the surface of the wire. The potential of the wire does change as the sheath of positive ions moves outward from the wire. This motion is governed by the mobility of the ions and by the type of variation of field strength with distance from the wire. For a cylindrical counter, the rate of change of potential of the wire is inversely proportional to the time, for times which are long compared to that taken by the multiplication process, that is, for times greater than 10^{-7} second. The rate of change of potential

[20] For further details regarding the processes by which the ionization is increased by the collision mechanism, see L. B. Loeb—"Fundamental Processes in the Electric Discharge in Gases," Wiley & Son, 1940.

difference between the electrodes of a counter with spherical geometry, such as is approximated by a point counter, will be inversely proportional to the square of the time. The shape of the voltage pulse from a counter is thus essentially determined by geometrical conditions.

Perhaps the situation may be better understood by reference to Fig. 8, which represents diagrammatically the electric

FIG. 8.

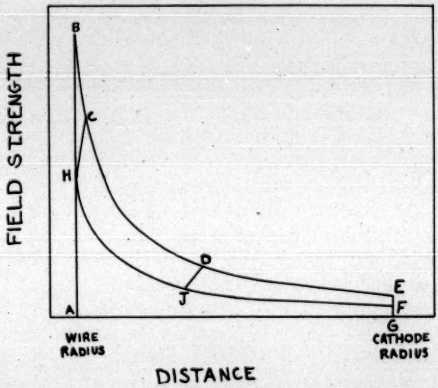


Illustration of the variation of electric field strength within a counter during the discharge.

field strength in a cylindrical counter as a function of the distance from the center of the wire. Initially, before a ray passes through the counter, the field varies inversely with the distance from the axis of the counter. The abscissa of the point *A* in Fig. 8 represents the radius of the wire and that of point *G* the radius of the cylinder. The field strength initially varies as shown by the curve *BCDE*. Since we consider the cathode to be at zero potential, the potential of the wire may be obtained by integrating the field from the wire to the cylinder, and the initial wire potential is represented by the area *ABCDEG*.

When an ion pair is formed within the counter, the electron will produce other ion pairs in the high field region of the

counter which we represent as the region between the wire and the cylindrical surface whose radius is given by the abscissa of the point *C*. Now let us suppose that the electrons formed in this region are drawn to the wire, leaving a positive space charge around the wire. The field strength outside the region is still unchanged, since the total charge within the cylindrical surface is unchanged, and is still given by the curve *CDE*. Within the region of space charge, the field is altered, however, and decreases from *C* to *H* as we approach the wire. The field strength at a point in the space charge region depends only on the amount of charge within a cylindrical surface through that point, since the field caused by a cylindrical shell of charge is zero inside the shell. The potential of the wire, after the electrons have been collected but before the positive space charge has moved, is again given by the integral of the field strength, or by the area *AHCDEG*. This is evidently nearly equal to the original potential of the wire and differs from it only by the small area *BCH*. As the positive ion sheath moves outward the field distribution changes, and when the sheath lies between the radii corresponding to the abscissæ of the points *D* and *J*, the field will be given by the curve *HJDE*, and the wire potential by the area *AHJDEG*. After the positive ions are collected, the field is *HJF*, and varies again inversely as the distance from the counter axis. The final potential is the area *AHJFG*.

This does not complete the story, however, since when the positive ions strike the cathode there are three possibilities for the subsequent behavior of the counter. The simplest case is that the positive ions eject no electrons from the cathode when they strike it. If this be true, then the positive ions are neutralized by electrons from the cathode cylinder and the counter wire recovers to its original potential by the leakage of charge across the high resistance connected to it, and the counter awaits the next count. This simplest case obtains in counters which contain alcohol or other organic vapors. The vapor affects the cathode surface in such a way as to make the probability of ejection of an electron by a positive ion very small. Alcohol counters have been commonly called "self-quenching" counters. This is an unfortunate term, since it is evident in the light of the mode of action described above

that the discharge is already quenched before the potential of the wire has appreciably changed. The alcohol has, more properly speaking, prevented the discharge from being reignited by secondary electrons from the cathode.

In the second case, let us suppose that the efficiency of production of secondary electrons by positive ions is high, so that many are formed when the positive ion sheath impinges upon the cathode. The effect which these secondary electrons produce depends upon the potential of the counter wire at the time of their formation. If the number of positive ions is large, and the capacity of the counter wire and the bodies connected to it is small, and the leakage resistance sufficiently high so that the charge leaking onto the wire is small, the motion of the positive ions across the tube will have resulted in a large change of potential of the wire. The change of potential may be so large, in fact, that the voltage across the counter falls below the Geiger-Mueller region. If this be the case, then the ionization by collision which the secondary electrons produce when they come into the high field region near the wire will be entirely negligible and no further change in the potential of the wire will result. The critical potential where the multiplication becomes negligible is less than the starting potential of the counter, but not very different from it. This can be seen from Fig. 1 where the curve rises very rapidly just before the beginning of region *E*, the Geiger-Mueller region. The counter wire can now recover to its original value and the counter is ready to record the next ionizing ray. When the potential of the wire falls below the starting potential of the counter, the counter is said to "overshoot"; in other words, a counter overshoots when the pulse size is greater than the overvoltage.

If the wire potential has not fallen below the critical potential of the counter for appreciable multiplication when the positive sheath strikes the cathode and ejects secondary electrons from it, we have the third and most complicated mode of discharge of a counter. The secondary electrons will in this case produce a large amount of ionization by collision close to the wire, and we have a repetition of the action of the original ion pair with the formation of a second sheath of positive ions around the wire. The second sheath of ions

travels across the counter and we have a further reduction of the wire potential. More electrons will be produced when the second sheath strikes the cathode, and the whole process will again repeat itself. The discharge thus becomes one of many stages. The amount of charge in the second sheath will be less than that in the first sheath, since the amount of charge is determined by the potential difference across the counter, and this is lessened in each successive stage. From the form of the variation of the amount of charge with potential, it can be shown that, if the first burst of positive ions is insufficient to bring the wire potential below the critical potential, no succeeding burst will be able to do so. The wire potential thus asymptotically approaches the critical potential. When the amount of charge per stage becomes small a new phenomenon enters the picture. The number of secondary electrons produced will be roughly proportional to the number of positive ions producing them, but when the number of electrons becomes small, it will be subject to large statistical fluctuations. When the average number of electrons per stage becomes as small as five, say, the probability that no electron is produced in a given stage of the process becomes appreciable. When no electron is produced, the chain of successive stages is broken and the counter wire can recover to its original potential.[21]

It should be pointed out that by changing the initial potential of the counter wire, or by altering the resistance or capacity, it is possible to make a counter deliver pulses of either the single or the multiple type. We shall not discuss here the experimental evidence for the correctness of the discharge mechanism described above.[22] Rather we shall analyze the desirable properties of a counter in terms of this picture, and endeavor to show what specific characteristics of the counter cathode must be attained in order that the counter shall be satisfactory.

The Efficiency of a Counter.—There are two classes of phenomena as a result of which a counter will not respond to

[21] W. E. Ramsey has recently obtained a series of oscillograph pictures showing both the single and multiple types of counter discharge which he intends to publish in an early issue of this JOURNAL.

[22] Some of the evidence has been summarized in reference 2.

every ray which passes through it. One class has to do with the fact that sometimes a discharge has taken place only a short interval of time before the ionizing ray passes through the counter, and the electrical circuits associated with the counter have not yet had time to recover sufficiently. We shall postpone the discussion of this class of phenomena to a later section. The other phenomena have to do only with the properties of the counter itself and do not depend upon whether or not a previous discharge has taken place. Geiger and Mueller [4] were the first to notice, and give the correct explanation for, an apparent insensitiveness of a counter under certain conditions. If we have a counter exposed to a constant source of radiation, and measure the counting rate as a function of the pressure of the gas in the counter, we find that at high pressures the counting rate is independent of the pressure. As the pressure is lowered, however, below a certain value the counting rate decreases and approaches zero at zero pressure. The explanation is a simple one. A high speed ionizing particle produces only a few ion pairs per cm. in the counter gas, which number is proportional to the pressure. At low pressures there is a finite probability that no ion pair is produced, and hence the ray will not be recorded. Since the events which produce ionization occur at random along the path of the ray, it is a simple matter to express this probability. If I is the primary specific ionization at atmospheric pressure, p the gas pressure in atmospheres, l the path length of the ray through the counter, then the average number of ionizing events that the ray will produce is Ilp, and the efficiency of the counter is $1 - \exp(Ilp)$. This expression must be summed over all paths through the counter to get the efficiency for all rays. The result will evidently be a very complicated one, depending of course on the angular distribution of the incident radiation. However, if the counter is long compared to its diameter, we can, for the purposes of design, substitute the diameter of the counter for the path l without serious error. Note that the quantity I is the number of ionizing events per cm. of path. The number of ion pairs per cm. is greater than this by roughly a factor of two depending upon the gas. This phenomenon has been utilized by

Danforth and Ramsey [23] and by Cosyns [24] to measure the primary specific ionization of cosmic rays. In these experiments, an exact calculation of the correct value of l to be used was made. The results are given in Table I. In each case

TABLE I.

The Primary Specific Ionization, I, of High Speed Particles.

Gas.	*I.*	Observer.
Hydrogen	5.9 cm.$^{-1}$	Cosyns [24]
Hydrogn	6.2	Danforth and Ramsey [23]
Air	21.	Danforth and Ramsey [23]
Helium	5.9	Cosyns [24]
Argon	29.4	Cosyns [24]

the measured value of the efficiency had the correct variation with pressure. These data establish three important facts: (*a*) a single ion is sufficient to produce a counter discharge, (*b*) the contribution of electrons from the walls of the counter is negligibly small, and (*c*) there is no loss of efficiency taking place as the result of the permanent capture of electrons to form heavy negative ions or other processes. There is some evidence that permanent capture does occur in pure oxygen [25] and perhaps in other gases.

It is thus true that the efficiency of the counter depends only on the gas filling and the counter size. Table II shows the approximate pressure of different gases which must be used to obtain a desired efficiency for a counter in which the mean path is one centimeter.

TABLE II.

Pressure of Gas (cms. Hg) for a Given Counter Efficiency When the Mean Path through the Counter is One Centimeter.

Gas \ Efficiency.	10%.	50%.	90%.	99%.
Hydrogen or Helium	1.4	9.0	29	59
Air	0.38	2.5	8.4	16
Argon	0.27	1.8	5.9	12

[23] W. E. Danforth and W. E. Ramsey, *Phys. Rev.*, **49**, 854 (1936).

[24] M. Cosyns, *Bull. Tech. Asso. Ing. de l'École Polytech. Bruxelles*, p. 173 (1936).

[25] W. E. Danforth, personal communication.

The efficiency of a counter for gamma radiation depends primarily upon another consideration, namely the number of secondary electrons which accompany the gamma radiation in the counter. This depends on the nature of the counter walls and on the energy of the radiation in a complicated manner. For a further discussion of the questions involved here the references listed in the footnote [26] are suggested.

Special Applications of Counters at Low Pressures.—Since it is possible to control the efficiency of a counter by varying the pressure of the gas used, some special applications of counters containing gas at a low pressure are possible. If the pressure be sufficiently low, the efficiency of the counter for single electrons of high energy is small, but the efficiency for groups of electrons passing through the counter simultaneously is much larger. In this way, showers of cosmic rays can be detected.

The usual counter arrangement for the detection of showers consists in measuring the simultaneous discharge of several counters so placed that no single ray may pass through all of them. Thus the probability of detection of a shower depends essentially upon the angular divergence of the shower rays, and there is strong discrimination against showers whose component rays are close together. This limitation is, of course, not present when counters of such low efficiency are employed that they respond only to groups of rays. Such experiments have been performed by Ramsey and Danforth,[27] who counted coincidences between two groups of counters, one above the other, containing hydrogen at a pressure of 2 cm. of mercury. The efficiency of the two groups of counters for n rays passing simultaneously through them may be easily shown to be $[1 - (1 - E)^n]^2$, where E is given by $1 - \exp(Ilp)$ as shown above. The efficiency of the two groups was thus 6.3 per cent. for single rays, 19 per cent. for two rays, 34 per cent. for three rays, 46 per cent. for four rays, and so forth.

If the efficiency of a counter is very low, then the expression $1 - \exp(Ilp)$ reduces simply to Ilp in the first approximation.

[26] C. G. Montgomery and D. D. Montgomery, JOUR. FRANK. INST., **229**, 585 (1940); J. V. Dunworth, *Rev. Sci. Instr.*, **11**, 167 (1940); F. Norling, *Phys. Rev.*, **58**, 277 (1940).

[27] W. E. Ramsey and W. E. Danforth, *Phys. Rev.*, **51**, 1105 (1937).

It is evident from this that such a counter exposed to radiation will measure a quantity proportion to the total ionization which the radiation produces, rather than the flux of rays through the counter.[28] In other words, the counter behaves like an ionization chamber. It should be noticed that under these conditions the counting rate becomes independent of the distribution in direction of the incident radiation, and the number of counts recorded becomes proportional to the volume of the counter, exactly as is the case with an ionization chamber.

A counter operating at low pressure might also be used for the detection of particles of high specific ionization, for example, slow protons, against a background of radiation consisting of high-energy electrons. Such an application does not appear to have been made up to the present.

The Size of the Voltage Pulse from a Counter Discharge.—In order that a counter be useful, it should deliver a large voltage pulse when it discharges. A counter is generally operated on the plateau of the characteristic curve at potentials from a few to several hundred volts above the starting potential. It is evident from the mechanism of counter action which has been described above that the potential of the wire will fall, when a discharge takes place, from its initial value to a potential in the neighborhood of the starting potential or below. Thus the size of the voltage pulse is equal to or greater than the over-voltage on the counter, and thus varies from a few to several hundred volts. If the capacity of the counter is large and the over-voltage small, the discharge will be a multiple one, and the potential will not go much below the starting potential. With a large over-voltage and a small capacity, the counter will overshoot, that is, the wire potential will fall below the starting potential. The discharge in this case takes place in a single stage. The phenomenon of overshooting was first recognized by Medicus,[29] and we reproduce as Fig. 9 some of his observations of pulse size as a function of over-voltage. The counter does not overshoot at low potentials, but does so at higher ones. Many investigators have doubted the existence of overshooting, but we have found it to be a property of

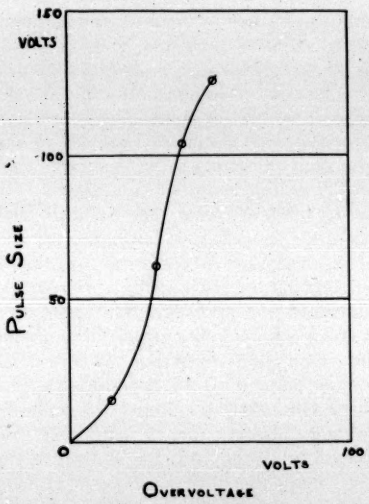
[28] S. A. Korff and W. E. Danforth, JOUR. FRANK. INST., **228**, 159 (1939).

[29] G. Medicus, *Zeits. f. Phys.*, **74**, 350 (1932).

all counters if the over-voltage is made sufficiently high and the wire capacity sufficiently small.

If a counter does not overshoot, the potential pulse from the wire is always the same size and *independent of the capacity of the wire*. There are, of course, small fluctuations in the

FIG. 9.



Pulse size as a function of overvoltage for a counter which overshoots.

pulse size, since the statistical nature of the breaking off of the series of discharges will not always allow the wire to assume the same final potential. When the counter does overshoot, the pulse from the wire is, in the first approximation,[30] *in-*

[30] The qualification has been added to take account of a secondary effect which is related to the propagation of the discharge along the length of the counter. If the electrons moved with an infinite velocity while they were producing ionization by collision, and if all the ionization were produced exactly at the surface of the wire, the pulse size would be exactly inversely proportional to the wire capacity. This is, of course, not true, and the counter wire will suffer some change of potential when the first avalanche of electrons is collected. This change of potential will decrease the multiplication of succeeding avalanches at

versely proportional to the capacity of the wire. Since the pulse size depends upon the over-voltage and capacity, it is, to a considerable extent, under the control of the experimenter, and can be adjusted to the best value for the problem in hand. The pulse size cannot, however, be increased without limit. The capacity of the wire cannot be reduced below a practical minimum value, nor can the over-voltage be too large. It is worth while to examine what happens at large over-voltages since this leads us to another aspect of counter behavior.

The first factor which limits us to not too high potentials on the counter is the occurrence of spurious counts. The counter characteristic curve will then be of the form shown by the solid line in Fig. 2. The rise at the upper end of the curve is generally quite rapid and rather sharply defines the maximum potential which can be applied to the counter. The causes for the occurrence of spurious counts will be discussed in the next section.

If the counter characteristic is of the form shown by the dotted line *C* in Fig. 2, somewhat different conditions prevail. It is to be noted that so far in the description of counter action, nothing has been said concerning the occurrence of a steady discharge in the counter. Indeed the steady corona discharge has essentially no bearing whatever upon the counting action, and it is quite a separate phenomenon. The most striking characteristic of the counter discharge is its transitory nature, and it has nothing in common with the static conditions which prevail in a steady discharge. Many investigators have failed to realize this essential difference in characteristics and have regarded the counter discharge as a sort of special case of the steady corona. This has led to much confusion of thought in the past. The occurrence of a steady discharge does influence the potential which can be applied to a counter, although not in the manner formerly thought to be the case. Let us suppose that we have a high potential between the wire and the

other points along the wire, because of the reduction in field strength. The amount of this reduction depends upon the capacity of the wire, and consequently the total amount of charge formed depends somewhat on the capacity. The magnitude of the effect and its variation with capacity seems to be well approximated by supposing that the counter wire possesses a "virtual" capacity, whose magnitude is not over 5 cms., which is to be added to the real wire capacity. A further investigation of the points involved here is under way at the present time.

cylinder of a counter and that a steady discharge is taking place between them. If the potential be decreased the current decreases, and at some potential, more or less well defined, the discharge will stop. Let us designate this minimum potential which will support the discharge by $V_{\text{min.}}$. The current at this potential is not zero, but has a finite value, $i_{\text{min.}}$, which is usually of the order of a microampere although it may be much larger or smaller. If we have a counter and a high resistance, R, in series, the minimum potential which can be applied to the combination which will support a steady discharge is $V_{\text{min.}} + Ri_{\text{min.}}$. Now it has generally been accepted that this potential is also the maximum potential which can be applied to a tube and have it act as a counter. We have been able to show [31] that, if the counter is overshooting at this potential, the voltage may be raised above the value which will support a steady discharge and, indeed, it may always be increased until we are limited by the occurrence of spurious counts. Thus the condition that the potential exceed $V_{\text{min.}} + Ri_{\text{min.}}$ is a necessary but not sufficient condition for a steady discharge.

Notwithstanding all this, the potential $V_{\text{min.}} + Ri_{\text{min.}}$ represents the *practical* limitation of the potential to be applied to a counter. For a counter to operate above this potential, it must overshoot. If it does not overshoot, the discharge will go over to the steady state. A counter operating at too high potentials will always come to a steady state of discharge eventually, although it may count for a long time before doing so. The transition to the steady state will happen when a count occurs in the time interval when the wire potential is recovering from a previous count and when this potential is not yet sufficiently high to have the counter overshoot. This time interval may be rather short, but ultimately a count will occur during it, however slow the counting rate may be.

Thus it is desirable to have the starting potential, V_s, as far as possible below $V_{\text{min.}} + Ri_{\text{min.}}$. To see how this can be accomplished it is necessary to inquire into the nature of the steady discharge. $V_{\text{min.}}$ is the minimum potential at which there will be built up a sufficient number of positive ions so that when they strike the cathode, there will be a high probability for the ejection of at least one secondary electron, so that

[31] Reference 2, page 1037.

the process may repeat itself. It is the probability considerations that are involved here that make the potential $V_{\text{min.}}$ not completely definite as was mentioned above. The current $i_{\text{min.}}$ is then simply the charge of the requisite number of positive ions divided by the time which they take to cross the counter. It is evident that it should be possible to control the relation between V_s and $V_{\text{min.}}$, since they depend on different properties of the counter. V_s depends upon the kind of gas and upon the photoelectric sensitivity of the cathode surface. $V_{\text{min.}}$ depends, on the other hand, upon the kind of gas and the probability that a positive ion striking the cathode will emit an electron from it. In most counters, $V_{\text{min.}}$ is slightly below V_s. However, in counters filled with alcohol vapor, $V_{\text{min.}}$ may be several hundred volts above V_s.

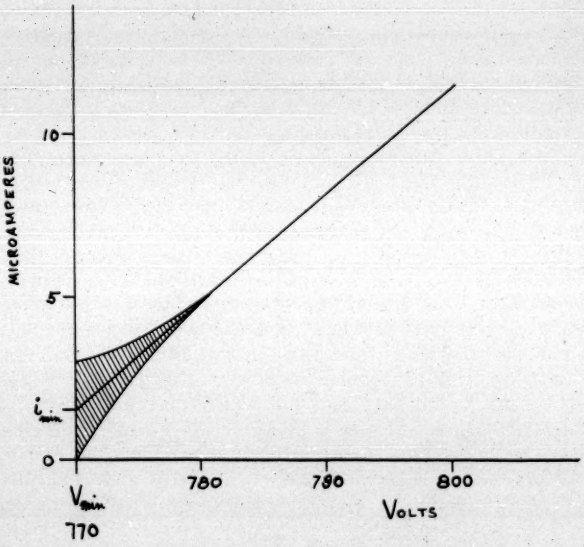
In counters where $V_{\text{min.}}$ is below V_s, the current near $V_{\text{min.}}$ should be subject to large fluctuations. This must be the case, since the number of electrons ejected by positive ions is small and will have large fluctuations. The number of positive ions which they produce is not independent of the number of these electrons, since the tube is operating below the Geiger-Mueller region, that is, in region D of Fig. 1. Thus the size of the groups of positive ions which cross the tube will vary widely among one another. Indeed, we may think of the minimum current as being that which is subject to fluctuations whose size is equal to the current itself. The frequency spectrum of these fluctuations will mostly consist of rather high frequencies, since the time of passage of a group of ions is small, so that an ordinary meter measuring this current will give a steady deflection. However, if observations are made with an oscillograph, these fluctuations are easy to observe. Figure 10 shows the results of some measurements made with a counter 1 cm. in diameter and 15 cms. long containing the gas mixture of 94 per cent. argon plus 6 per cent. oxygen at 9 cms. pressure. The figure shows the current as a function of voltage across the tube, and also the limits of the fluctuations [32] which occur.

[32] This limit was determined simply by measuring the width of the pattern on the oscillograph screen. The accurate definition of just what this limit means involves the same sort of reasoning as would be necessary precisely to define the potential $V_{\text{min.}}$, and becomes obvious if one considers the matter a while. Space forbids a discussion of these questions here.

We have been unable to make a similar test on counters where $V_{\text{min.}}$ is greater than V_s, as in alcohol counters, since in every counter which we have examined the phenomenon is seriously interfered with by spurious counts.

Thus we see that to obtain a counter where $V_{\text{min.}} + Ri_{\text{min.}}$ is larger than V_s there are two possibilities. First, the value

FIG. 10.



The current of the "steady" discharge condition in a counting tube. The shaded area represents the magnitude of the fluctuations in the current.

of R may be made large. R cannot be increased indefinitely, however, since the speed of recovery of a counter after a discharge has taken place is determined by the time constant, RC, of the wire, and it is undesirable to have this quantity too large. The second possibility is to increase both $i_{\text{min.}}$ and $V_{\text{min.}}$ by obtaining a cathode surface from which the ejection of electrons has a very low probability while its photoelectric

sensitivity to the photons which are produced in the multiplicative process is not affected. This may be accomplished by the addition of an organic vapor, such as alcohol, to the counter gas. This is not a completely satisfactory solution to the problem, however, since the alcohol will eventually chemically decompose under the conditions in which a counter is used and the counter characteristics will change with time. There is opportunity for much more experimental investigation along these lines which should result in counters with considerably better properties than those which we have today. It should be noticed that an alteration of the properties of the cathode in regard to secondary emission will change $i_{\text{min.}}$ proportionally more than $V_{\text{min.}}$, as long as $V_{\text{min.}}$ is less than V_s. This is illustrated by the shape of the curves in Fig. 1 in the region D.

The Self-Excitation of a Counter.—Unfortunately, Geiger-Mueller counters have the property of spontaneously discharging without the passage of a ray through them. The occurrence of such spurious counts is the most common reason for the failure of a counter to be satisfactory, and their elimination is of primary importance in the construction of a counter. All counters show their effects to some extent, but it is possible to make the contribution of spurious counts entirely negligible over a fairly wide range of potentials. The increase in the counting rate as the potential across the counter is raised is illustrated in Fig. 2, where the counter characteristic begins to rise at the point B. Spurious counts most commonly limit the extent of the plateau of the characteristic curve, and in bad counters, their occurrence can not only cause the disappearance of the plateau, but their effects may be quite large at potentials below the Geiger-Mueller region.

The phenomena which give rise to the self-excitation of a counter have been the object of much investigation in the past, although the primary application of the results of these investigations has not been to Geiger counters, but to the glow discharge lamps which are in such common use today. It was found that when the potential was applied to such a glow lamp, the discharge did not start immediately, but there was a statistical distribution of lags in time before starting. It was also shown that it was not necessary to wait for an ion pair

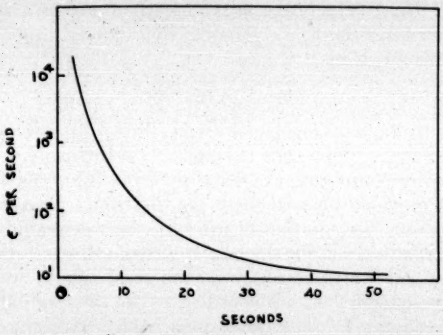
formed by external radiation to occur between the electrodes, but that such initial ionization was furnished by the lamp itself. Moreover, the mean time lag in starting was found to depend on the occurrence of a previous discharge of the lamp, and upon the length of time and the amount of current which had passed through the lamp during this previous discharge. It was, therefore, postulated that these effects could be explained in terms of a surface phenomenon of the electrodes by which there were spontaneously emitted electrons which caused the breakdown of the lamp into a glow discharge. The previous discharge of the lamp established this surface condition, and to an extent depending upon the current and the length of time during which it flowed. In other words, the glow lamp was started when a "spurious count" occurred, and a glow lamp which starts with small time lags is one having a large number of spurious counts.

The mechanism by which the delayed emission of electrons takes place is not certainly understood, but the chief processes are well established. The emission arises from particles of non-conducting material which have become charged either by photoelectric emission from the light accompanying the discharge, or by positive ion bombardment. The delayed emission then either consists of electrons which are pulled out of the cathode in the large electric field produced by the positively charged bit of non-conducting matter or we have a phosphorescent process whereby photons are emitted which produce photoelectrons from other surfaces in the counter. Probably both of these processes may be important depending upon the nature of the foreign matter and the cathode surface. The non-conducting matter can also become discharged and does not necessarily cause a spurious count Thus the probability that a count be followed by a spurious one decreases with time. A recent investigation of these phenomena has been made by H. Paetow,[33] and we present an example of his results in Fig. 11. In a tube having plane parallel nickel electrodes and filled with argon, a discharge current of one microampere was allowed to pass for one second. The discharge was stopped by removing the potential, and after waiting a time, t_w, the potential was reapplied. The discharge

[33] H. Paetow, *Zeits. f. Phys.*, 111, 770 (1939).

did not rekindle immediately but a short time lag was present. The reciprocal of the mean value of this time lag represents the rate of emission of electrons. In Fig. 11 this rate of emission of electrons (rate of occurrence of spurious counts) is plotted on a logarithmic scale as the ordinate as a function of the time t_w. These effects may be increased by many orders of magnitude if the surfaces of the electrodes are dirtied or if they are coated with a non-conducting oxide such as MgO. Indeed, surfaces have been produced which show the emission of enough electrons so that the current is measurable with a galvanometer as

FIG. 11.



The delayed emission of secondary electrons, the "Pætow" effect.

long as 24 hours after the discharge has been stopped.[34] Paetow found a large effect even when the electrodes consisted of two tungsten spirals which could be heated to incandescence to clean and outgas them. Although the heating reduced the effect by about a factor of ten, it was still very evident.

In the light of the large magnitude that these effects can have it is rather surprising that it is possible at all to prepare counters in which spurious counts are absent. The great importance of the cleaning process in the preparation of counters now becomes evident, and the care that should be taken cannot be over-emphasized. It is also evident why the use of

[34] L. Malter, *Phys. Rev.*, **50**, 48 (1936).

magnesium or aluminium electrodes should be avoided, since their oxides are always present and non-conducting. Spurious counts can also arise from the insulating glass walls of the counter, and as previously mentioned, such walls should not be too close to the sensitive volume of the counter.

Since the delayed emission of an electron is most probable just after the preceding discharge or count, the counts in a counter which shows this effect are not distributed at random in time. Events which are distributed at random in time are separated by intervals having a characteristic frequency distribution. If τ be the average interval between counts, then the probability that there be a count in an interval of time dt is dt/τ. The probability that there are no counts in a time interval t is $e^{-t/\tau}$. Hence the distribution of time intervals is given by

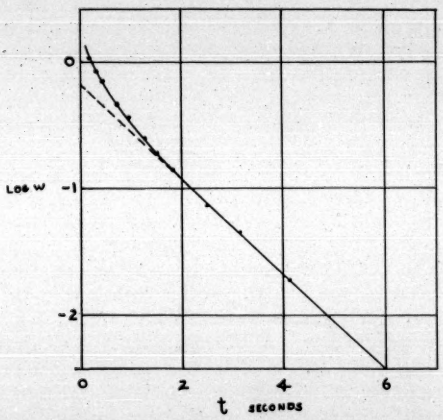
$$Wdt = 1/\tau e^{-t/\tau} dt.$$

We see that $\log w = \log 1/\tau - t/\tau$ is a linear function of t. If spurious counts are present they will most probably occur just after another count, and the distribution of intervals will have an excess of short intervals over the distribution given above. The frequency distribution of intervals between counts forms a rather sensitive test for the occurrence of self-excitation. In Fig. 12 are shown some observations of Medicus [15] of such a frequency distribution. The ordinates are the quantity $\log w$, and abscissæ are t. The deviations from a straight line are very marked for short time intervals and are the result of spurious counts. In fact, if the succession of counts from a counter is made audible one can readily learn to recognize the sound of a counter giving random counts, and can frequently tell from just listening when there are many spurious counts present. The most characteristic feature of a random distribution is the occurrence of relatively long intervals during which no count takes place.

The increase with potential across the counter in the number of spurious counts is the result of the increased amount of charge which is passed in each count. However, since a spurious count is just as likely to follow another spurious count as a real one, the *proportion* of spurious counts will increase with counting rate. Thus the rise in counting rate at the

upper end of the counter characteristic should be faster than expected and this is in harmony with observation. Likewise, we may draw the important conclusion that *if an appreciable number of spurious counts are present, the counting rate of a counter will not be proportional to the intensity of radiation falling upon it.* In other terms, if an intensity of radiation will cause n real counts in a counter, the counter, when the phenomenon of self-excitation is present, will not be proportional to n but will have the form $n + an + bn^2 + \cdots$,

FIG. 12.



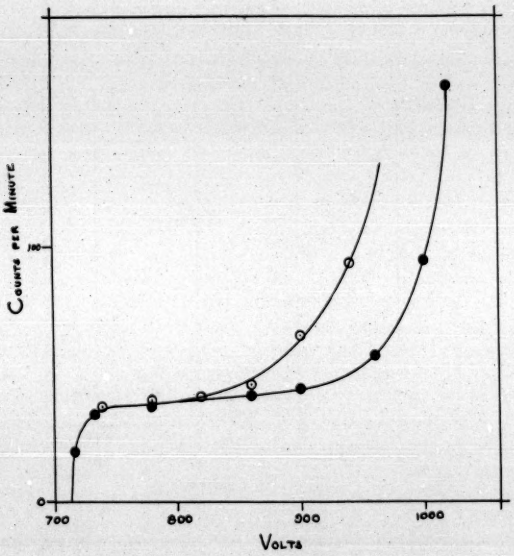
The frequency distribution of the intervals between counts in a Geiger-Mueller. The deviation from linearity for short intervals is caused by spurious counts.

where the terms an, bn^2, etc., are the contribution of the spurious counts.

The effect of the amount of charge flowing in a counter upon the number of spurious counts can be easily demonstrated by a simple experiment. Suppose that we observe a characteristic curve of a counter in which we know that overshooting takes place. The discharges all take place in one stage and a certain amount of charge at a given potential crosses the counter per second. Now if we add a large capacity to the counter wire, the discharges will have a multiple

character and the amount of charge crossing the counter per second will be large. Hence we should expect the rise of the characteristic curve which is caused by spurious counts to take place at a lower potential. Figure 13 represents the characteristic curves of a counter 1 cm. in diameter and 15 cms. long which is filled with 94 per cent. argon and 6 per cent. oxygen to

FIG. 13.



Counter characteristics for a counter without capacity added to the wire (lower curve) and with 25 cm. capacity added (upper curve).

a pressure of 9 cms. of mercury with and without an additional capacity of 25 cms. attached to the wire. The expected increase caused by spurious counts is very evident. It is worth while to point out that with an alcohol counter the addition of capacity will not cause the discharges to become multiple and will leave the amount of charge crossing the counter unchanged. We should, therefore, not expect to find the effect shown in Fig. 13, and this is found to be the case.

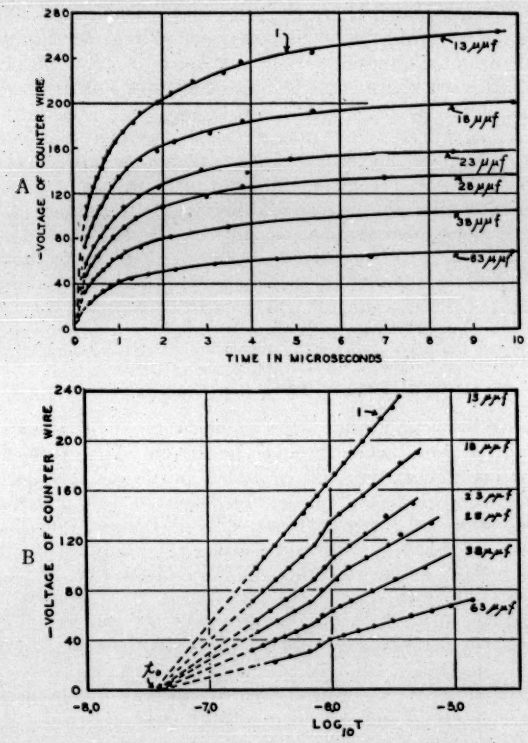
The Speed of a Counter Pulse.—It is naturally desirable that a counter break down rapidly and then recover quickly to be ready to record the next ray through it. According to the mechanism of counter action described above, the fall of potential of the wire is the result of the motion of the positive ion sheath from the neighborhood of the wire to the cathode, and is determined by the mobility of the ions and the geometry of the counter. The exact form of the voltage pulse has been the subject of a recent experimental investigation by W. E. Ramsey,[35] who has measured directly the potential of the counter wire down to times as short as 2×10^{-7} second after the wire potential has started to change. For the method by which this was done, the reader is referred to the published account of the experiments. The experiments gave the result that the potential of the wire as a function of time may be expressed by the equation:

$$V = V_0 - \beta Q/C \log (t/t_0 + 1),$$

where V is the potential of the counter wire at the time t, V_0 the wire potential when $t = 0$, Q the amount of charge formed in the counter, C the wire capacity, and β and t_0 empirical constants which depend on the dimensions of the counter and the mobility of the positive ions. Q is, of course, a function of V_0, but not β or t_0. This expression is valid only for the first stage in the case that the discharge is a multiple one. Figures 14 and 15 illustrate some of the data taken. It is seen that the breakdown of a counter is an extremely fast process: so fast indeed that for most experiments the breakdown time can be entirely neglected. For experiments in which this time may be important, it is essential that the proper values of the counter potential and the capacity of the wire are used. The time for the counter wire to arrive at a given potential depends exponentially upon the capacity and the quantity Q. Since it depends on the ratio of the two, however, it is possible to compensate somewhat the bad effects of a large value of C by increasing Q, which can be done by increasing V_0. For a series of counters filled with gas at different pressures, if V_0 was adjusted so that the counters gave pulses of the same size, that is, the same value of Q, the potential variations of the

[35] W. E. Ramsey, *Phys. Rev.*, **57**, 1022 (1940).

FIG. 14.



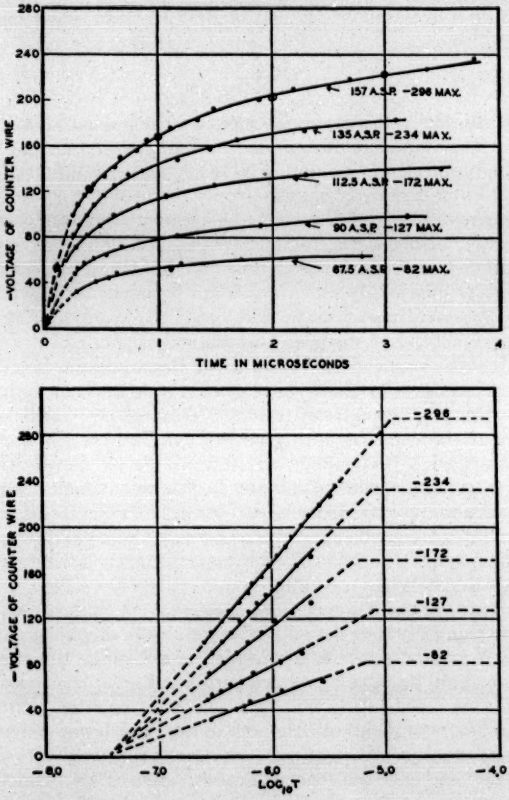
A series of breakdown characteristics of a counter with various capacities added to the wire. The capacity marked on each curve represents the total capacity of the wire and all bodies connected to it.

counter wire were very much the same. There is thus no optimum pressure to obtain a fast breakdown.

If we call $V_0 - V = \Delta V$, and denote the pulse size by $\Delta V_{max.}$, then $\Delta V_{max.} = Q/C$. If instead of the parameter β, we use the quantity t_m defined by

$$1/\beta = \log (t_m/t_0 + 1),$$

FIG. 15.



A series of breakdown characteristics of a counter for several values of the overvoltage. The numbers attached to the curves are to be interpreted thus: 157 A.S.P.—296 MAX. means that the initial potential difference across the counter was 157 volts above the starting potential and that total potential charge of the wire was 296 volts.

then we can write the expression for the potential change of the counter wire in the approximate form

$$t/t_0 = (t_m/t_0)\Delta V/\Delta V_{\max.}.$$

For counters whose cathodes are 1 cm. in diameter with wires 0.003 inch in diameter the parameters have the approximate values:

$$t_m = 10^{-5} \text{ sec.}$$
$$t_0 = 3 \times 10^{-8} \text{ sec.}$$

From this approximate expression we can estimate, with an accuracy generally sufficient for design purposes, what time will be required for a counter to reach a given potential. It should be emphasized that the proper value of $\Delta V_{max.}$ to use in this expression is the potential change in the *first* stage of the discharge. Only if the counter is overshooting is this the total potential change of the wire. If a multiple discharge is taking place the times will be *much* longer, and greater the greater the capacity since more stages will occur. For further details reference should be made to the original paper.

After the counter wire has fallen to its minimum potential, it recovers to its original value as charge leaks back onto the wire through the high resistance. This recovery will be an exponential one having a time constant RC where C is the wire capacity and R the leakage resistance. R is generally of the order of 10^9 ohms, while C may be 10^{-11} farads, which results in a time constant of the order of 10^{-2} second. Thus the recovery of a counter is a much slower process than the breakdown, and this time generally determines the maximum counting rate of the counter. When a counter is used with one of the types of vacuum tube quenching circuits, this recovery may be reduced to something of the order of 10^{-4} second. In alcohol counters where R can be made much less than 10^9 ohms the time of recovery may perhaps be reduced still further. That no other process goes on during the recovery of a counter than the leakage of charge across the resistance has been tested by accurate measurements of the form of the recovery curve.[36]

It is evident that the desirable potential at which to operate a counter is that at which it is just beginning to overshoot. The potential should be at least large enough to make the counter overshoot, since then the pulse consists of a single fast breakdown. The potential should be, however, low enough so that the overshooting is a minimum, so that the counter can recover as fast as possible.

[36] W. E. Ramsey and M. R. Lipman, *Rev. Sci. Inst.*, 6, 121 (1935).

Time Lags in Counter Discharges.—The wire of a Geiger-Mueller counter does not always begin to change its potential immediately after the formation of an ion pair in the counter, but a few per cent. of the discharges may have a time lag as great as several microseconds.[37] This delay is well explained by the following mechanism. Occasionally all the electrons which are produced by the passage of the ray through the counter will be captured by an electronegative component of the gas and travel toward the central wire as negative ions rather than as electrons. When they arrive in the neighborhood of the wire, the negative ions will be broken apart by collisions in the high field [38] and the electrons will be set free and proceed to ionize by collision in the usual manner. The time of travel of the negative ion may be as large as several microseconds and this constitutes the time lag. The lag thus depends entirely upon the nature and the pressure of the gas in the counter and has no bearing upon the rest of the counter mechanism. It should indeed be possible to reduce them to the order of the time taken for the electron to traverse the counter, that is, to less than 10^{-7} second. The way to accomplish this should be to employ gases which have been purified very carefully from all electronegative constituents. It is not sufficient to employ tank hydrogen, for example, although the lags in this gas are less than in the usual argon-oxygen mixture.[39]

Time lags of the order of a microsecond form the limitation on the minimum resolving time that can be used for counter experiments. The speed of breakdown of the counter does not impose a limitation even at much smaller times.

TESTING A COUNTER.

In the preceding sections we have discussed what the properties of a good counter are, and upon what factors they depend. We wish to consider now what tests can be made

[37] C. G. Montgomery, W. E. Ramsey, D. B. Cowie, and D. D. Montgomery, *Phys. Rev.*, **56**, 635 (1939); J. V. Dunworth, *Nature*, **144**, 152 (1939).

[38] L. B. Loeb, *Phys. Rev.*, **48**, 684 (1935).

[39] Some experiments by the authors are in progress which furnish good evidence that the lags are produced by the mechanism described above. The observations also serve to determine the capture probability of an electron in the argon-oxygen mixture.

upon a counter to determine its performance. The final check on good performance comes, of course, only from the use of the counter in the actual experiment. The tests which we wish to consider here are to be regarded as preliminary ones, which can generally be rapidly made.

A great deal of information can be obtained from the measurement of the counter characteristic. We can determine the starting potential, the correct operating range, the counting rate on the plateau, and obtain some idea, from the rise of the characteristic at high potentials, of the prevalence of spurious counts. Hence it is recommended that the characteristic curve be always measured.

Tests of Counter Efficiency.—The efficiency of the counter can be very well predicted from a knowledge of the dimensions of the counter and amount and kind of gas in it. An excellent rough check of the efficiency is the counting rate of the counter when it is operated on the plateau of the characteristic. If the counter is long in comparison with its diameter, few rays will traverse the counter whose paths do not cross a given plane through the counter wire. Thus the counting rate should be almost proportional to the area of this given plane, or to the counter length times the counter diameter. Once the normal counting rate per unit area in a given location has been determined, the measurement of the counting rate of a counter can be used to estimate roughly the efficiency. This counting rate will, of course, depend upon the thickness of the glass wall of the counter, and since the cosmic radiation is not uniform in direction, the rate depends also on the orientation of the counter. For example, in our laboratory at the Bartol Research Foundation, the counting rate of a horizontally placed counter with glass walls of standard thickness and of 100 per cent. efficiency is 2.8 per minute per cm^2.[40] One can estimate the efficiency in this way to approximately 10 per cent.

A method for determining the efficiency more accurately has been described by Street and Woodward.[41] They employ

[40] The radioactive content of the surroundings as represented by this figure seems to be exceptionally low. For example, in different rooms at Sloane Physics Laboratory, Yale University, the corresponding counting rate varies from 5 to 9 per minute per cm^2.

[41] J. C. Street and R. H. Woodward, *Phys. Rev.*, **46**, 1029 (1934).

the counter to be tested as an interior member of a cosmic ray telescope having at least three coincidence units. If the solid angle defined by the telescope is kept constant, then the ratio of the number of coincidences observed with the counter to be tested to the number observed when it is disconnected is equal to the counter efficiency. This method determines the "overall" efficiency of the counter. It measures not only what fraction of the rays are missed because they do not produce an ion in the counter, which fraction we call E_p, but also the fraction lost because they passed through the counter while it was in an insensitive state, recovering from the occurrence of a previous count. If σ be the minimum time interval between the occurrence of two rays which are both recorded, then σ is called the *recovery time* of the counter. It is, of course, dependent upon the leakage resistance and capacity of the counter wire and upon the sensitivity of the recording circuit. The efficiency of a counter from this factor is E_σ, and is equal to $e,^{-\sigma n}$ where n is the counting rate of the counter. The overall efficiency of the counter is the product $E_\sigma \cdot E_p$. In the actual use of this method, other corrections are necessary and the reader is referred to the original paper for a discussion of them.

Street and Woodward also determined the effective area of the counter by displacing it out of line with the other members of the telescope. They found that while the counter was sensitive over the whole diameter, the sensitivity diminished at the ends of the counter length. This is caused by the weakening of the field strength at the ends of the cylinder. If the over-voltage is of the order of a hundred volts, the effective length is less than the whole length of the counter by roughly the diameter of the counter. This end effect will obviously diminish as the potential in the counter is increased. For this reason the plateau of the counter characteristic will never be perfectly flat, but will rise with potential. In the most accurate work, these effects must be taken into account.

Test for Size of Counter Pulse.—There are many ways in which the size of a counter pulse can be determined, but all depend very much upon the particular circuit used to record the counts. It is, therefore, not profitable to discuss them in detail. It might be mentioned that a cathode-ray oscillograph

is useful in this connection. It is scarcely necessary to make a test of this nature at all, since the pulse size must be at least equal to the over-voltage of the counter.

Tests for Spurious Counts.—As mentioned above, the flatness of the plateau of the characteristic curve is one good measure of the number of spurious counts. Secondly moreover, the counting rate on the plateau should have a value not greater than normal (within 10 per cent.) as described under the rough tests for counter efficiency. The most useful rough test is the following: By bringing up a source of radioactive material one increases the counting rate of the counter many times. On removal of the source, the counting rate should fall *at once* to its normal value. Since the number of spurious counts depends on the amount of charge passing through the counter at a previous time, if spurious counts are occurring the rate will persist at a value greater than normal for a short time after the radioactive material is removed, and one can frequently detect this simply by listening. The proportionality of the counting rate to the intensity of incident radiation can also be used as a criterion for the absence of spurious discharges. Duffendack, Lifschutz, and Slawsky [42] have employed this method of determining the reliability of a counter.

The most sensitive test is to determine the distribution in time of the counts as they occur. We have already stated that a practiced observer can tell by simply listening to the recording mechanism whether the distribution is a random one or not. It must be kept in mind that with a random distribution the most probable time interval between counts is zero and there is always a tendency for counts to occur in groups of two or three. The only certain way is to record the time distribution in some manner, such as by recording the individual counts on a moving tape. Two vacuum-tube circuits for accomplishing the same purpose have been described.[43] These circuits will record simultaneously the total number of intervals and the number of intervals greater than an assigned value.

Test of Speed of Breakdown.—To insure that we have fast discharges which are single (not of the multiple type) we have

[42] O. S. Duffendack, H. Lifschutz, M. M. Slawsky, *Phys. Rev.*, **52**, 1231 (1937).

[43] A. Roberts, *Phys. Rev.*, **57**, 564, 1069 (1940). R. L. Driscoll, M. W. Hodge, A. Ruark, *Rev. Sci. Instr.*, **11**, 241 (1940).

seen above that all that is necessary is to be sure that the counter is overshooting. Thus all that is necessary is to measure the size of the pulse, and see that it is sufficiently large. For a more accurate determination of speed of breakdown, the vacuum-tube circuit described by Ramsey [35] may be used, or the simpler device of measuring the pulse size as a function of the recovery of the circuit [2] may be resorted to.

COUNTERS USED AT POTENTIALS BELOW THE GEIGER-MUELLER REGION.

We have confined ourselves in the above to a discussion of counters used in the Geiger-Mueller region of potentials. It will be recalled that this region is characterized by the fact that the same amount of charge is produced in the counter independently of the number of ion pairs which initiate the process. This region of potentials is illustrated as region *E*, Fig. 1. In view of the possible applications to studies of nuclear physics, we should like to say something about counters used at potentials below the Geiger-Mueller region. Such counters have been variously called Geiger-Klemperer [3] counters, proportional counters, multiplication counters, and sub-threshold counters. Counters in which the high field region is produced near a point or a small sphere, designated as point counters, are generally used in this way. The distinguishing feature of such counters is that the voltage pulse appearing on the counter wire is not independent of the initial number of ions. If the potential across the counter is sufficiently low so that it lies in region *C* of Fig. 1, the voltage pulse is proportional to the initial number of ions. If the voltage is so high as to fall in region *D*, the voltage change of the wire will not be proportional to the initial number of ions, the departure from linearity being greater, the greater the number of ions formed. The relations which are indicated in Fig. 1 can be expressed in a somewhat different way. S. A. Korff [44] has recently made some observations with a counter 2 cms. in diameter and 20 cms. long filled with boron trifluoride at a pressure of 11 cms. of mercury. The counter was provided at one end with a thin glass window through which alpha particles could be shot into the counter. The amount of

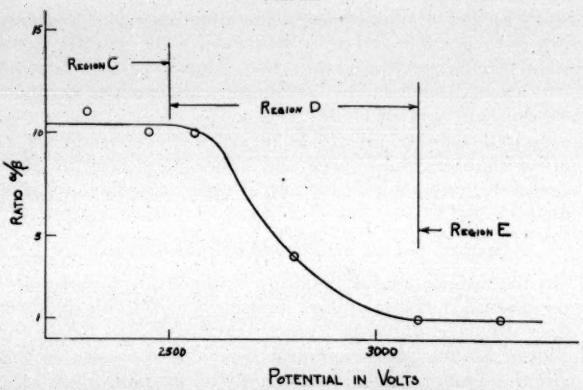
[44] Experiments described in "Report on the Work of the Bartol Research Foundation, 1939–40"—W. F. G. Swann, JOUR. FRANK. INST., **230**, 281 (1940).

ionization which they produced in the counter was known, since their range within the sensitive volume could be determined. This ionization amounted to 16,000 ion pairs. Likewise the counter could be exposed to intense gamma radiation from radium. This radiation produced beta particles within the counter which liberated various numbers of ion pairs. The maximum amount of ionization would be produced by a beta particle whose range was just equal to the maximum path length within the sensitive volume of the counter. This ionization was 1500 ion pairs. Thus the ratio of the alpha to the maximum beta ionization was 10.7. Now if a high potential was applied to the counter so that it behaved as a Geiger-Mueller counter in region *E*, Fig. 1, the pulses resulting from the alpha and beta particles would be equal. As the potential of the counter was lowered into region *D*, Fig. 1, the pulses would become unequal, and the ratio of alpha pulses to the beta pulses would increase with decreasing potential. When the potential was lowered still further, the proportional region *C* was entered, and the size ratio of the pulses should become independent of counter potential and equal to the expected value. Figure 16 shows the actual observations. The maximum value of the ratio observed is equal to that expected.

These observations and the relationships illustrated in Fig. 1 are well explained by the same mechanisms which we have indicated as important in the Geiger-Mueller region. At low potentials the ionization by collision will be confined to the points along the wire to which the original ions are drawn by the field. At higher potentials the active regions spread more and more along the length of the tube by the action of photo-electrons from the cathode until the tube becomes filled along its whole length. When this is the case, we enter the Geiger-Mueller region and the pulses all become alike. It should be pointed out that spurious counts can occur in sub-threshold counters as well as in Geiger-Mueller counters and by the same mechanism. Since the amounts of charge which generally flow across a proportional counter are much smaller than in Geiger-Mueller counters, it is much easier to eliminate the spurious counts in sub-threshold counters. Moreover, a counting tube can break over into a steady discharge without

the occurrence of any Geiger-Mueller region at all. If the probability that a positive ion eject an electron from the cathode be sufficiently high, then a steady discharge will start when the multiplication becomes large enough. The current of this discharge will, at first, depend upon the number of original ions which start the process, but it will build up to a value independent of the intensity of radiation falling upon the

FIG. 16.



The transition between the region of proportional amplification of the initial ionization in a counter (region *C*) to the Geiger-Mueller region (region *E*). The ordinates are the ratios of the sizes of the voltage pulses produced by alpha-particles shot into the counter through a thin window to the sizes of the pulses produced by beta particles whose ranges are equal to the length of the counter; the abscissæ are the potential differences across the counter.

counter as more and more ions are formed in the tube by this radiation.

Neutron Counters.—An important application of sub-threshold counters has been their use to detect slow neutrons.[45] A counter filled with boron trifluoride gas and operated below the Geiger-Mueller threshold may be used with a recorder which is too insensitive to detect the voltage pulses which electrons or cosmic rays produce. When a slow neutron disintegrates a boron nucleus of mass ten, considerable energy is released which appears as ionization. The reaction which

[45] S. A. Korff and W. E. Danforth, *Phys. Rev.*, **55**, 980 (1939).

takes place is

$$B^{10} + n = Li^7 + He^4 + 2.5 \text{ MeV}.$$

The 2.5 MeV which are released produce roughly 7×10^4 ion pairs, and this may be amplified by the counter to a value large enough to be easily recorded. Counters coated on the interior with a layer of boron have also been employed [46] to detect neutrons.

Neutrons may also be detected by using a counter in the Geiger-Mueller region whose cathode consists of a material which is made radioactive by neutrons. The counter is exposed to the neutron beam and then removed and the activity of the cathode determined. Counters with silver cathodes work excellently in this way.[47]

It should be remembered in regard to the construction of neutron counters that pyrex and nonex glass contain quite appreciable amounts of boron and are good absorbers for slow neutrons.

CIRCUITS FOR USE WITH GEIGER-MUELLER COUNTERS

In the applications of counters to the study of particular problems, it is necessary to use some electrical circuit to detect and record the counter discharges. Many devices have been employed for this purpose, and it is beyond the scope of this report to do more than indicate, in a bibliographical form, the general types of circuits which have been used. We confine ourselves to descriptions published in readily available journals, and no attempt is made to be exhaustive. For a general discussion of counter circuits, reference may be made to the article "Geiger Counters" by H. V. Neher in "Procedures in Experimental Physics," by John Strong and collaborators, Prentice-Hall, Inc., New York, 1938. Some papers dealing with special applications are listed below.

A. Vacuum-Tube Quenching Circuits.

I. A. GETTING, *Phys. Rev.*, **53**, 103 (1938), "Multivibrator Geiger Counter Circuit."
T. H. JOHNSON, *Rev. Sci. Instr.*, **9**, 218 (1938), "Circuits for the Control of Geiger-Mueller Counters and for Scaling and Recording Their Impulses."

[46] E. Fünfer, *Ann. der Physik*, **29**, 1 (1937); S. Kawata and M. Ito, *Proc. Phys.-Math. Soc. Japan*, **22**, 116 (1940).

[47] G. L. Locher, *Phys. Rev.*, **50**, 1099 (1936).

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Glass Reinforcement for Concrete (*Engineering*, Vol.150, No. 3899).—The system of using glass instead of steel for reinforcing concrete developed by Mr. A. W. Soden, A. R. I. B. A., and Mr. John A. Lincoln has been subjected to preliminary tests by Dr. W. S. Marshall, A. M. Institute C. E. in the Structural Laboratory of the City and Guilds College, South Kensington. These tests showed that glass should not be used as reinforcement when impact loads are likely but confirm that for static loading glass makes a suitable reinforcement. Also it was shown that there were limitations in the length of the glass strips available for reinforcement, and it was stated that further investigations were proceeding with the object of overcoming this and other difficulties. Some of these have been completed by Dr. Marshall. The objects were to determine the resistance moment of beams 12 in. by 7 in. and 9½ in. by 4½ in. sections; to determine the grop length or "lap" required for glass reinforcement; and to design a beam of long span using short lengths of glass with the lap previously determined and to test such a beam. The concrete used throughout the tests was a 1 : 2 : 3 mix of rapid hardening Portland cement, well graded clean river sand, and Thames ballast. For concrete between the glass strips a ⅜ in. aggregate was used. The glass reinforcement consisted of various lengths of strips up to 9 ft. long, ¼ in. thick and 4½ and 5⅞ in. wide. In a cross section of concrete 12 by 7 in., 4 to 8 strips were used. These tests confirmed the earlier tests with regard to static loading. A feature was the consistency of the behavior of the material. The lap tests indicated that 2 ft. was sufficient lap for the glass used in these beams. There was a tension failure, the fracture section occurring in each case at the end of the lap. It was shown that the ultimate resistance moment of a glass reinforced beam can be expressed empirically by the formula $M = 1250\,td^2$, where t is the total thickness of glass plates used and d is the depth of the beam measured to the edge of the glass reinforcement.

R. H. O.

ELECTRICAL CONTACT RESISTANCE.

BY

G. WINDRED.

INTRODUCTION.

The subject of electrical contact resistance is a very extensive one, including as it does a wide variety of incidental phenomena, such as thermal effects, coherer action and the behaviour of different kinds of surface films. A truly comprehensive treatment of electrical contact phenomena would necessarily include such subjects as the Peltier effect (Jean Charles Peltier, 1785–1845), the Seebeck effect (Thomas Johann Seebeck, of Berlin, 1770–1831) and the Thomson effect (Lord Kelvin, 1824–1907). Although these phenomena are of importance from the purely physical standpoint, they belong to the domain of thermo-electricity rather than to electrical contact theory, and have only an indirect bearing on electrical contact resistance.

The fundamental laws of thermo-electricity may be stated briefly as follows:

If a circuit be constructed of two wires of different homogeneous metals A and B and the junctions between them maintained at different temperatures, a current will flow in the circuit. Such a current is called a thermo-electric current, and the circuit is called a thermo-couple. Study of the phenomenon has shown that the couple is the seat of an e.m.f. giving rise to the observed current, and that this e.m.f. remains substantially constant as long as the conditions remain unchanged. This is the Seebeck effect.

When current flows in a thermo-couple, the temperatures of the junctions change, unless the change is prevented by adding or subtracting heat from the junctions. The amount of heat which must be applied in this manner is proportional to the current; not to the square of the current as in the case of Joulian heat, and the amount of heat generated or absorbed in the respective junctions is known as the Peltier heat. It is

dependent upon the two metals and the temperature of the junction, and is unaffected by other circuit conditions.

It was originally thought that the Peltier heat was the only source of electrical energy available for maintaining the thermo-electric current. The accuracy of this assumption could be checked by comparing the Peltier heat with the watt-seconds absorbed in the circuit, as represented by the product of e.m.f. and quantity of electricity. Experimental difficulties prevented this, but the idea was examined theoretically by Lord Kelvin, who concluded that it was untenable. It followed from Kelvin's investigations that the temperature distribution in the wire should be changed by the flow of current. This effect was finally established by Kelvin after many years of research on the problem, and the heat transference involved in the effect became known as the Thomson heat. This heat is represented by the disturbance of temperature distribution which occurs when a current flows in a metal between two points at different temperatures.

Another important contact phenomenon is known as the Volta effect, discovered by Alessandro Volta (1745–1827), Professor of Natural Philosophy at Pavia. It was found by Volta that when different metals are brought into contact an e.m.f. is developed between them. The effect may be explained on the basis of the electron theory on the principle that different substances vary in the ease with which they give up their electrons. In the case of zinc, for example, the release is very free, and if zinc is brought into contact with copper a number of electrons pass from the zinc to the copper. The zinc accordingly acquires a positive potential with respect to the copper, which receives a negative potential due to the assemblage of electrons transferred from the zinc. Detailed study of the Volta effect, or indeed of any of the thermo-electric phenomena, leads rapidly into difficulties of analysis. It may be said that there are several branches of these subjects which have not yet reached a state of finality, and there is still room for differences of opinion regarding the precise nature of the physical processes involved. A comprehensive treatment of the entire domain, including discussions of modern work, has been given by Bridgman.[1]

[1] P. W. Bridgman, "The Thermodynamics of Electrical Phenomena in Metals," New York (Macmillan), 1934.

In connection with coherer action, and its significance from the viewpoint of electrical contact theory, it is interesting to record the following words of S. P. Thompson: "The conduction of powdered metals is remarkable. A loose heap of filings scarcely conducts at all, owing to the want of cohesion, or to the existence of films of air or dust. But, as discovered independently by Calzecchi-Onesti and Branly, it becomes instantly a good conductor if an electric spark is allowed to occur anywhere within a few yards of it. The resisting films of air are broken down by minute internal discharges in the mass. A very slight agitation by tapping at once makes the powder non-conductive." [2] At the time these words were written, there was very little experimental evidence for the existence of the films of air or dust to which reference is made. Recent research has shown that the phenomenon of coherer action depends upon very obscure effects, and it is only during the last few years that thorough experimental analysis of these effects has been carried out.

The subject is very closely connected with the electrical properties of surface films, which are of particular importance in all studies of electrical contact phenomena; especially those relating to contact resistance. The physical properties of surface films on metals have received considerable attention from metallurgists, and the theory of oxide formation is now well understood. Accurate experimental methods have also been developed for the measurement of the thickness of surface films of different kinds.[3]

With regard to the general effects which determine electrical contact resistance, such as the shape and condition of the contact surfaces and the pressure acting upon them, almost every conceivable aspect of the subject has been dealt with since the end of last century, when the quantitative aspect began to assume importance owing to increasing electrical development in different directions. The records of these researches are distributed very widely, and in many

[2] "Elementary Lessons in Electricity and Magnetism," London (Macmillan), 1929, p. 430.

[3] A well annotated survey of the subject from the viewpoint of the metallurgist is given in the book "Review of Oxidation and Scaling of Heated Solid Metals" (various authors), London (Stationery Office), 1935. Re-issued 1937.

languages, so that there has been much duplication of effort in the formulation of the basic principles of contact resistance phenomena.

GENERAL REVIEW.

Electrical contact resistance may be defined as the resistance offered to the flow of current during its passage across the interface between two conducting materials which are in contact with each other. This contact resistance is not necessarily the same as the electrical resistance of a joint between two conductors, since the arrangement of the joint may be such as to cause an increase of resistance due to distortion of the lines of current flow from one conductor to the other. The actual value of the contact resistance depends upon several conditions relating to the respective materials and the manner in which they are employed.

There are four principal conditions which determine the contact resistance in a given case:

I. The kind of materials used for each contact member.
II. The condition of the contact surfaces.
III. The shape of the contact surfaces.
IV. The mechanical pressure acting upon the contacts.

With regard to materials, it is found in general that materials of high conductivity, such as silver and copper, give a lower contact resistance than those of lower conductivity, such as iron and tungsten. Experiments have shown, however, that other factors exist which are far more important in determining the contact resistance. The hardness of the materials and the state of their surfaces, for example, have considerable influence upon the contact resistance between given metals.

The condition of the contact surfaces is represented by the degree of cleanness, whether they are rough or smooth, and whether any form of lubricant has been applied to them. As a general rule, a very smooth contact will give a greater contact resistance than a slightly rough one, owing to the fact that the latter type of surface results in more points of contact for a given pressure. The effects of a lubricant of any kind are twofold: In the first place its presence may prevent or hinder the formation of surface films, such as oxides, and

secondly, it may have an effect upon the conductivity of the interface between the contacts. Surface films have a very marked influence upon contact resistance, and a large proportion of the researches on contact phenomena have been concerned with the properties, electrical and otherwise, of such films. The resistance of the noble metals to the formation of surface films has led to their extensive use as contact materials.

The importance of the shape of contact surfaces is associated with the mechanical pressure acting upon them. It is found that low contact resistance occurs when the specific contact pressure is high, so that in general this condition is obtained with small contact surfaces, such as would be given by cylinders lying crosswise or by spheres in contact with each other or with plane surfaces. Lengthy researches on the relationship between contact pressure and resistance have shown that for a given type of contact these two quantities are related in a very definite manner.

It is now generally considered that contact resistance may be explained on the basis of Ohm's law as an example of metallic conduction, and that the conductivity of any gaseous or fluid films which may exist at the interface does not appreciably affect the conditions. This conception of contact resistance does not recognise the possibility of electronic conduction across free space between the contacts, although such a possibility connot be ruled out until experiment and theory show that the electric fields which may exist are not sufficiently great to cause conduction of this kind.

The contact resistance between metallic surfaces is influenced to a considerable extent by the mechanical properties of the respective metals, since these properties determine the magnitude of actual contact between the metals with a given applied pressure. In general, the contact resistance is inversely proportional to some function of the pressure; the exact function being dependent upon the shape and elastic properties of the contacts and their surface condition. The deformations of various types of surface under the effects of pressure were examined in some detail by Heinrich Hertz,[4] Professor of Physics at Bonn, and his work in this connection

[4] H. R. Hertz, "Gesammelte Werke," Leipzig, 1892, vol. I, pp. 155, 183.

formed the basis of researches, notably by L. Binder and E. Contius, on the relationship between the mechanical pressure and contact resistance of metallic surfaces, wherein it was necessary to know the laws connecting the area of the contact surface and the applied pressure.

THEORY OF CONTACT RESISTANCE.

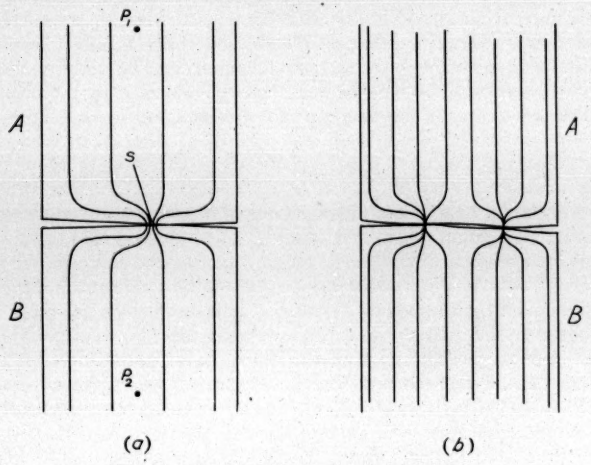
If two bodies are brought into contact under very low pressure they will touch first at an isolated point, and if it be assumed that no surface films of any kind are present, it can be said that under these conditions there is actual contact between the two bodies. If the bodies are electrical conductors it is then possible for a current to pass from one body to the other.

In its passage from one body to the other the current encounters resistance. This resistance is known as the contact resistance, and its value depends upon a variety of factors which have already been mentioned. It will be evident that when the respective bodies or contacts make actual connection at an isolated point, the flow of current will be restricted at that point, where the current density will consequently be greater than in either of the respective contacts, assuming, as is normally the case, that the cross-section of the bodies at right-angles to the direction of current flow is large in comparison with the area of the point of contact.

The lines of current flow between two bodies having point contact with each other are represented in Fig. 1, in which (*a*) and (*b*) respectively illustrate the conditions for one and two points of contact. When there are more than one contact points, there may be electromagnetic interactions between the lines of current flow if the contact points are close together, but otherwise this effect may be neglected. It will be understood that theoretically any number of contact points may exist, according to the shape of the respective surfaces, the mechanical properties of the materials, and the forces existing at the contact face.

In general, it may be stated that when an electric current flows across the interface between two contacts there exists between the contacts a difference of potential whose magnitude is dependent upon the current strength and the elec-

FIG. 1.



Streamline effect of current flow through point contacts.

trical resistance between the contacts. In passing across the interface the current flows through one or more regions of contact, and at these regions there is constriction in the lines of current flow which causes a lengthening of these lines and hence increases the effective resistance between the contacts.

An interesting analogy has been suggested by L. Binder [5] on the basis of hydrodynamics in order to present a picture of the manner in which the lines of current flow arrange themselves when the current passes through isloated conducting regions. Binder compares the current flow under these conditions with the flow of a fluid through holes in a separating wall between two containers, and concludes that under given conditions the same principles apply to the electrical and hydrodynamic current flow.

It should be pointed out that the hydrodynamic analogy should not be taken too far, since there are details of fundamental difference between the two processes. It will be

[5] "Der Widerstand von Kontakten," *Elek. u. Masch.*, H. 38, 1912.

realised, for example, that in the case of fluid flow the resistance originates in the friction between the imaginary tubes of flow, whereas in the electrical case there is not always interaction between the current elements. The chief value of the analogy lies in the fact that it allows of a pictorial representation of the current distribution, and consequently helps in forming an analysis.

The total contact resistance between two bodies may be defined quantitatively as follows: Two bodies A and B of the same material and of homogeneous composition are allowed to make contact with each other. It is assumed that actual effective electrical contact occurs at an isolated point or surface S whose dimensions are very small in relation to the dimensions of the bodies A and B. The conditions are represented by Fig. 1(a). If V is the voltage drop between points P_1 and P_2 on either side of the interface and separated by a considerable distance and if I is the current which flows from one body through surface S into the other body, then the total contact resistance is given by

$$R = V/I \text{ (ohms)}. \tag{1}$$

This resistance consists virtually of three independent resistances:

(1) The resistance offered to the flow of current during its passage across the interface at S.
(2) The resistance represented by the streamline effect of current flow in conductor A due to the constriction at S.
(3) The resistance represented by the same streamline effect in conductor B.

If these three components of the total contact resistance are represented by r_1, r_2, r_3, we have

$$R = r_1 + r_2 + r_3 \tag{2}$$

and in the special case where conductors A and B are electrically identical, so that the streamline effects are the same in each,

$$R = r_1 + 2r_2 = V/I, \tag{3}$$

$$V = I(r_1 + 2r_2), \tag{4}$$

$$I = V/(r_1 + 2r_2). \tag{5}$$

Analysis of the conditions between surfaces with several points of contact may be carried out as follows:

It is firstly assumed that the surfaces in question possess n small points of electrical contact of circular shape with radius a, and that these points are distributed inside a large circle of radius A. The remaining parts of this circular area do not conduct electrically across the interface.

The individual conductances L, L_1, L_2, etc. of the respective point-contacts may be simply added together if the points are distributed sufficiently far apart, but if strict accuracy is required, attention must be given to the fact that the lines of current flow from the respective points of contact have a mutual interaction upon each other.

From the mathematical viewpoint the problem is analogous to that of determining the electrostatic effects due to the charges on circular discs; corresponding to the contact areas, when each of the discs has the potential P relative to points at an infinite distance. It can be shown [6] that the capacity of a circular disc of radius a is equal to $2a/\pi$. If, therefore, the charge of each disc is q and its potential P_1, we have for one such disc

$$q = P_1 2a/\pi. \tag{6}$$

In our particular case, however, it is necessary to consider another potential P_2 which is caused by the remaining discs included in the area A. As an approximation, the value of P_2 may be arrived at by assuming that the total charge nq is distributed uniformly over the entire area containing the discs. We then obtain

$$nq = P_2 2A/\pi. \tag{7}$$

The potential applicable to our case is evidently equal to half the contact voltage, on the assumption of symmetrical contacts, so that if this voltage is V we obtain

$$P = \tfrac{1}{2}V = P_1 + P_2 = nq(\pi/2an + \pi/2A). \tag{8}$$

It may be noted here that in the electrostatic problem we are concerned with a potential function φ having the value

[6] See, for example, Sir J. H. Jeans, "Electricity and Magnetism," 5th Ed., Cambridge, 1927, p. 249.

$\frac{1}{2}V$, and the following equation represents the conditions at the surfaces:

$$-\int \frac{d\varphi}{dn} \cdot df = 2\pi q. \tag{9}$$

In the problem of conductivity in one contact we are concerned with a similar potential function $\varphi = \frac{1}{2}V$ and if λ is a constant representing the electrical conductivity we also have

$$-\lambda \int \frac{d\varphi}{dn} \cdot df = I. \tag{10}$$

where $\lambda \frac{d\varphi}{dn}$ represents the current density at the interface.

Comparison between the equations (9) and (10) shows that in the contact conductivity problem $I/2\pi\lambda$ plays the same part as q in the electrostatic problem. In our case $q = \frac{1}{2}VC$, so that $I/2\pi\lambda = \frac{1}{2}VC$.

If in equation (8) we substitute $I/2\pi\lambda$ for nq we obtain

$$R = \frac{V}{I} = \frac{1}{2an\lambda} + \frac{1}{2A\lambda}. \tag{11}$$

For the complete contact system, comprising contacts A and B for example, the resistance represented by each part of equation (11) must be made up of two parts, one for each contact, so that we have in general

$$R = \frac{1}{4an\lambda_A} + \frac{1}{4A\lambda_A} + \frac{1}{4an\lambda_B} + \frac{1}{4A\lambda_B}. \tag{12}$$

This equation is based on the assumption that the same potential exists over the entire contact surface, so that all the points of actual contact possess the same potential.

If, as is usually the case, A is large in relation to na, the last portion of equation (11) can be neglected. This omission allows of R being expressed as a function of n, since it is possible to establish the relationship between n and a by assuming that all the contact points are loaded mechanically up to the flow pressure f of the contact material. In this case we have

$$P = n\pi a^2 f, \tag{13}$$

so that

$$a = \sqrt{P/n\pi f}. \tag{14}$$

Substitution of this value of a in the equation

$$R = \frac{1}{2an\lambda}, \tag{15}$$

representing an approximation to equation (11), gives

$$R = \frac{1}{2\lambda\sqrt{P/n\pi f}} \tag{16}$$

or

$$R = \frac{\sqrt{\pi f}}{2\lambda\sqrt{P}} \cdot \frac{1}{\sqrt{n}}. \tag{17}$$

This form of the equation shows that the resistance becomes smaller as the pressure increases, on account of increased area of the individual regions of contact. All the terms of equation (17) are constants, with the exception of P and n, which are definitely related to each other, so that we may write in general

$$R = k/\sqrt{P}. \tag{18}$$

This equation is in agreement with the experimental results of E. Contius,[7] who showed that with high pressures, ranging between 1000 and 5000 kg., the simple equation (18) satisfactorily represented the relationship between resistance and pressure for all types of contact and for any kind of finish of the surfaces.

EFFECTS OF SURFACE FILMS.

Only metals prepared carefully under high vacuum can be regarded as having a pure metallic surface, free from extraneous films. In air, the precious or so-called noble metals are rapidly covered with a surface film, one molecule thick, of oxygen or water. In the case of common metals the thickness of the film increases in the course of time, at a rate depending upon the local conditions. In the case of copper,

[7] "Der Einfluss der Grösse des Druckes und der Fläche auf den Kontaktwiderstand," Dissertation, Dresden, 1929.

for example, oxidation occurs at a rapid rate under normal atmospheric conditions.

Researches have shown that copper exposed to air for one hour at 50° C. undergoes no visible change and very little increase of weight, but similar exposure at higher temperatures produces change of colour and an increase of weight which rises rapidly with the temperature. The increment of weight at 200° C. is about sixteen times the value corresponding to 100° C. At temperatures higher than 50° C. in the case of copper, oxygen can penetrate through the oxide to the metal below, and thus the film quickly attains sufficient thickness to become visible. It has been found that although sulphur is a normal constituent of the tarnish film formed on copper at ordinary temperatures, the films contain much more oxide than sulphide.

When copper is heated in air, the oxidation process yields a surface film which is non-porous and which hinders the meeting of oxygen and metal owing to its unnatural state of lateral compression. Under certain conditions, the rate of passage of oxygen inwards through this film and the rate of diffusion of metal outwards will be inversely proportional to the thickness, so that the rate of oxidation falls off with the time.

Interesting results have been obtained in the case of the rarer metals. Molybdenum, for example, has a volatile oxide, which may sometimes evaporate as fast as it forms, leaving the metal clean, but this only occurs in a stream of oxygen. Mercury, silver, platinum and gold, all of which find application for electrical contacts, form oxides whose dissociation pressures reach the atmospheric value at rather low temperatures, above which no oxidation can be expected without increased oxygen pressure. The evidence available does not exclude the possibility of noble metals oxidising at low temperatures, but it is uncertain whether all the oxygen molecules are capable of combining.

In most cases the rate of oxidation of non-ferrous metals with respect to time is governed by the simple relation $W^2 = Kt$, where W is the amount of oxide formed. Although the precise mechanism and laws of oxidation have not yet been firmly established, the fundamentals are well understood, and

copper, for example, has been studied at temperatures between 50° C. and the melting point. It is interesting to note that the oxidation of copper, as well as of most other metals, is considerably accelerated by the presence of chlorine, probably owing to the intermediate formation of chlorides and oxychlorides causing a loose-structured oxide film abnormally permeable to oxygen. Considerations of this kind are interesting in relation to suggestions which are put forward from time to time for the use of various gases as quenching media for arcs occurring in switchgear.

At this stage, reference may be made to a popular idea relative to silver, i.e. that the tarnish film which forms upon exposure to air is an oxide of silver. The following extract from J. R. Partington's "Textbook of Inorganic Chemistry" (3rd Edn., 1931) is of interest in this connection: "Silver is not oxidised by pure air or oxygen, either in the cold or when heated, and is an example of a noble metal. In ordinary air it slowly tarnishes and becomes covered with a thin adherent film, which exhibits the colours yellow, blue and black with increasing thickness. This film is composed of silver sulphide Ag_2S formed by the decomposition, in presence of oxygen, of hydrogen sulphide in the air."

It has furthermore been shown by E. F. Kingsbury [8] that the common monoxide of silver is of very high resistance, even when strongly compressed in thin discs. It may be concluded that the reason for the comparatively low contact resistance of silver, even when in a tarnished state, lies in the fact that the sulphide film has a much lower electrical resistance than, for example, the oxide film on copper. Alternatively, the difference in behavior may be due to the fact that the physical properties of the two films are essentially different. It has beens suggested that whereas the copper oxide is very firmly attached to the parent metal, the surface film of silver is easily removed by relatively slight friction, or may actually become decomposed by heat. Any or all of these effects would account for the observed differences in behavior in the two cases.

Further observations concerning the physical properties of

[8] "The Use of Noble Metals for Electrical Contacts," *Bell System Technical Journal* Reprint B. 298, April 1928.

surface films belong more properly to the subject of contact metals. In the meantime, however, we may consider the electrical characteristics of such films.

The most usual types of film encountered in practice are those consisting, for example, of an oxide of the contact material, and having a thickness of several molecules. If we assume for simplicity that such a film, of thickness x, on a contact face is brought into contact with the perfectly clean metallic surface of a second contact, and that the contact area takes the form of a circle of radius a, the contact resistance will be approximately given by

$$r_1 = kx/\pi a^2, \tag{19}$$

where k is the specific resistance of the surface film.

COHERER ACTION.

The phenomenon of coherer action is a very interesting one, and plays an important part in the theory of electrical contacts. The action may broadly be defined as a variation in conductivity between bodies in contact which can be caused either by a variation of mechanical pressure between the bodies or a variation in the potential difference applied to the bodies. When the coherer action occurs, the electrical resistance between the two bodies falls to a relatively low value, and this condition is maintained, even if the potential is removed, until the bodies are separated, for example, by vibration as in the case of the telephonic coherer.

In general, coherer action is a phenomenon associated with very low contact pressure, such as might be produced by small metallic particles resting upon each other. It will be understood that the pressures of contact encountered in coherers of most types are of very low order of magnitude. A considerable amount of research has been carried out on contacts operating under very low pressures, with the object of obtaining information on the basic principles of coherer action and the electrical properties of surface films. An account of this research in its application to contact problems will be given later.

A small but definite time interval is required for coherer action. Authorities are by no means in agreement concerning

the duration of this interval, which is probably dependent upon a variety of factors relating to the conditions of measurement. Modern determinations of the time interval range between 10^{-6} and 3×10^{-3} second.

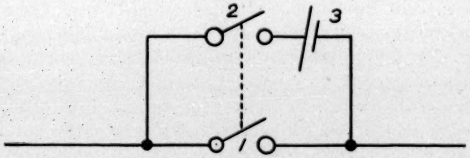
It has been found that coherer phenomena are chiefly dependent upon the nature and thickness of surface films, rather than upon the conducting bodies which carry these films. The true coherer effect is reversible, which means that it can be repeated indefinitely, by suitably varying the conditions giving rise to it. It is possible, however, under certain conditions for coherer action to develop into a form of electrical breakdown which results in the welding together of the respective contact surfaces. The nature of the bond thus formed depends upon a variety of factors, and may be such as to require considerable mechanical force for the subsequent separation of the contacts.

The importance of coherer action from the practical viewpoint arises from the fact that the phenomenon is of significance in certain industrial applications of electrical contacts. As an example may be mentioned the contact difficulties which may be experienced in connection with wave-length changeover switches on radio receivers. These switches normally handle very small currents at low voltage, so that the conditions are conducive to coherer action when there is a possibility of a surface film forming on the contacts. If the formation of this film is prevented by frequent rubbing together of the contacts during normal operation of the switch, the effect will not occur, but under normal circumstances it is possible for a film to form, and in this case the occurrence of coherer action may seriously affect the operation of the equipment.

It has been suggested that to overcome this difficulty in radio receiver switches it would be possible to connect in parallel with the switch contacts a circuit consisting of a second pair of contacts and a suitable source of direct current which would ensure effective breakdown of the surface films. From the diagram of this arrangement given in Fig. 2 it will be noticed that when the switch is closed, a local circuit through the D. C. source and the respective switch contacts is completed as well as the main circuit.

It might be supposed that the use of a condenser in parallel with the switch might overcome the difficulty in the case of a low-voltage D. C. circuit, since the discharge current from the condenser would ensure breakdown of surface films and

FIG. 2.



Prevention of coherer action in low-power circuit. 1—main contact; 2—auxiliary contact; 3—direct current source.

lead to the establishment of effective contact. It is found, however, that the conditions introduced by the discharge are detrimental to the contacts. When the contacts first touch, and consequently represent very imperfect conductivity, the discharge is enabled to take place, and may readily give rise to considerable surface disturbance of the contacts without materially changing the conditions of conductivity in the normal position.

In order to overcome these difficulties it is necessary to adopt a contact design which will give high specific contact pressure, preferably combined with a wiping or sliding action which will ensure removal of surface films or deposits. It is also necessary to employ noble metals, such as platinum or platinum-iridium alloys, which do not acquire harmful surface films and are sufficiently hard to withstand considerable friction without undue wear.

An interesting and practical example of coherer action may be mentioned here. It is convenient and general practice in connection with ornamental electric lighting to connect a large number of low voltage lamps in series for operation from the lighting supply. In the event of failure of any lamp, all the remaining lamps would cease to operate, owing to the breaking of the series circuit, and it might be a tedious and lengthy process to locate the faulty lamp. This difficulty has been overcome by arranging a quantity of metal particles in the

form of a coherer between the terminals in the socket of each lamp. In the event of a lamp burning out, its terminals are subjected to the full line voltage; the coherer short-circuits under the action of this increase of voltage and thus reëstablishes the circuit, so that the remaining lamps continue to operate. It will be understood that under these conditions the voltage across the terminals of each of the remaining lamps is increased beyond the value corresponding to normal working, but if the number of lamps is large the proportion of increase in the voltage applied to each remaining lamp is generally too small to have any considerable effect upon the life.

As an example of the importance of surface films from the electrical engineering viewpoint, it is interesting to record the results of some experiments by Holm [9] with Telefunken coherers. Under normal conditions they had a resistance of from 5 to 20 $\times$ 10^6 ohm, and withstood a potential of about 1 to 1.5 volts. An increase of this potential by 0.2 volt reduced the resistance to about 10,000 ohms or less when the current was limited to about 10^{-5} ampere. If the current was allowed to reach a value of the order of 0.02 amp., the resistance usually fell still further to only a few ohms.

Holm carried out experiments on copper and nickel contacts which had been exposed to the atmosphere several days in order to acquire an appreciable surface film. In these experiments, very low contact pressures, of the order of from 0.0005 to 0.01 gram, were employed in order to observe the coherer effect. This was found to consist in a permanent reduction of resistance. When the resistance did not fall below about 30 ohms the effect was attributed to the conveyance of the current through poorly conducting surfaces, which Holm calls *b*-surfaces. When the resistance fell to a value between approximately 10 and less than 1 ohm the conditions were regarded as an example of metallic conduction between so-called *a*-surfaces. It was concluded that both kinds of coherer action can be produced either by increase of voltage or mechanical pressure. Increase of pressure facilitates further coherer action.

It has been noticed that in the case of low-resistance co-

[9] *Wiss. Veröff. a.d. Siemens-Konzern*, 7, H2, 1929, § 14.

herer action it is possible for the metals to become so welded together that a pressure considerably in excess of the original contact pressure is required for their separation. It was found, for example, that a force of about 0.006 gram was required to separate copper contacts after repeated application of 0.10 volt under a mechanical pressure of 0.002 gram obtained by allowing one contact to rest with a part of its weight upon a second contact.

GENERAL THEORY.

The majority of oxide films have a specific resistance of the order of 10^6 (ohm-cm.). They present, in accordance with equation (19), very high contact resistances which, according to the surface thickness, can withstand appreciable voltages. However, as soon as a critical puncture voltage for the particular surface has been reached, an immediate change takes place, which manifests itself in a considerably improved conductivity. It is said under these conditions that a breakdown has occurred and the surface is visibly disturbed at the place where conduction has taken place. If the current is limited sufficiently, however, the change is of a particular kind. Increased conductivity is arrived at after a period without current flow (which is not of course the case with normal breakdown conditions) and the change is not discernible at the surface, even with a magnification of two hundred times. These are the conditions corresponding to coherer action.

It was suggested by O. Lodge that the coherer action was actually due to a kind of bridging effect by means of metal atoms through the otherwise isolated surface layer. These ideas have been thoroughly substantiated by the researches of R. Holm and his collaborators.

It has been shown [10] that for the coherer action a field strength f is necessary, and that the coherer voltage F is proportional to the thickness, y, of the layer. It is also shown that f is dependent upon the surface layer, and very little upon the metal. This field intensity f is the same as is otherwise referred to as breakdown field strength.

It has also been shown that the coherer action results in the production of metallic bridges through the insulating

[10] Holm, Güldenpfennig and Störmer, *Wiss. Veröff. aus dem Siemens-Konzern*, 10, Heft 4, 1931, p. 20.

surface, and it is these bridges which cause the improved conductivity.

Strong arguments for the existence of such bridging elements are:

1. Contacts between which the coherer action has taken place usually give metallic resistance-voltage characteristics with small temperature coefficients as if the metal were impure, or possessed a spongy structure which restricted the free passage of the conducting electrons.

2. The melting voltage V_m—i.e. the highest voltage which a contact resistance can withstand—is also suitable for bridges. These bridges build up to sufficient magnitude to withstand directly the voltage V_m, i.e. they are able to withstand directly the current without melting.

3. Certain researches on coherer contacts have allowed of the calculation of the bridging dimensions. The mechanical bonding of such contacts has also been measured, and found to be of the magnitude that would be expected from the mechanical strength of the bridges.[11]

The bridge diameter is found, in the cases more easily examined, to be of the order of 0.3μ, and is therefore very small. It will consequently be appreciated that the existence of the bridges can not, up to the present, be detected microscopically. The bridges remain in contact, and conduct the current until they are disturbed by movement of the contacts.

We will now deal with another aspect of the breakdown theory, viz., that of free ions. It might be thought that the formation of the bridges commences as soon as the field is applied. As mentioned previously, the field intensity f is necessary for the coherer action, but this process is dependent on various circumstances which will be dealt with shortly. We can, however, come to the following definite conclusions.

The oxide of nickel possesses two such coherer field strengths, f_1 and f_2. At certain points of the surface the one applies, and at other points of the surface the other value is necessary for coherer action. This applies in the case of a freshly prepared nickel oxide layer. Greater values of f are required, according to how old the layer is—i.e. whether days or weeks. It is possible to assume that the coherer action is

[11] Loc. cit., § 9.

associated with free ions, and that in nickel oxide there are ions with two different degrees of freedom. One kind is moved by a field $f_1 = 1.1 \times 10^6$ V/cm., while the other requires a value of $f_2 = 1.4 \times 10^6$ V/cm. In the course of time even the most free ions acquire the positions corresponding to f_2.

R. Holm was originally of the opinion that the first step in coherer action was the release of free ions, and that the second step was the arrangement of such ions into conducting metallic elements, or filaments. It seems plausible that the first element, or elements, will not carry the applied current, in which case local melting occurs, thus producing adequate material for the formation of the conducting bridges, and in consequence of interruption of the restoring field there is an accumulation of material which results in the establishment of thicker bridges. This process goes on until these bridges are able to carry the appropriate current.

It has been observed that the melted particles resulting from the breakdown are readily uged by the field into the negative direction of current flow, so that the bridges are actually produced from the cathode metal if this melts earlier. In accordance with the present ideas the bridges build themselves best out of the metal representing the anode of the contact, and which can therefore send positive metal ions into the pores of the insulating layer. If contacts of the order: metal—surface layer—carbon, are examined, the bridges are produced less readily, and represent a higher resistance if the positive current emanates from the carbon than when it flows in the opposite direction. Measurements have confirmed this effect.[12]

The hypothesis of bridge formation by free ions, when given in this form, is very plausible, when it is not complicated by further considerations which must now be considered.

1. A layer of lacquer, which can contain no free ions, exhibits coherer action just as well as the nickel oxide layer, although about ten times the field strength is required. The linear relationship between the coherer voltage and the layer thickness in this case is not clearly established, and it is possible that an accurate study of the conditions would reveal

[12] Loc. cit., §§ 8, 9.

fundamental differences between the coherer processes in the nickel oxide and in the lacquer.

2. The quantities f_1 and f_2 unfortunately are not sharply defined, since a field some 10 per cent. smaller can cause coherer action when it is allowed to operate for a longer time—e.g. a few seconds.[13]

It is possible to imagine that a free ion at certain times acquires increased freedom, and that in the case of slight coherer action it is actually a matter of awaiting such moments. It is also possible to examine the hypothesis that the coherer action is a form of heat penetration which requires a certain accumulation time. In this connection it can be noted that the coherer effect commences on the application of f_1 and f_2 in about 0.003 second, and that with high frequency voltage the effective value corresponds approximately to the normal D.C. coherer voltage.

The following two objections apply to this idea—

(1) That the limitation of current has no influence whatever upon the coherer voltage;
(2) That the ambient temperature corresponds to a temperature range wherein f_1 and f_2 are not sensitive to temperature.

The question may now be asked whether these observations on coherer action which prohibit the conception of ion collision as the principal effect, are in opposition to the breakdown theories of Joffé [14] and Von Hippel.[15] It is possible to visualise the following two kinds of breakdown:

Form I is initially a coherer action, but degenerates finally in consequence of absence of current limitation into a breakdown in which the normal coherer bridges are vapourised by the heavy current, and thus give rise to an eruptive dissipation of energy, conducive to the formation of arcs. This eruption in the contact is of the form which is referred to as a breakdown.

[13] Loc. cit., end of § 6.

[14] A. Joffé, J. Kurchatoff and K. Sinelnikoff, "The mechanism of breakdown of dielectrics," *Massachusetts Inst. of Techn. Pubns.*, **62**, 1927, No. 117. A. Joffé, *Phys. Zeit.*, **28**, 1927, p. 911; *Trans. Faraday Soc.*, **24**, 1928, p. 65.

[15] A. von Hippel, *Zeits. f. Phys.*, **67**, 1931, p. 707.

Form II may be introduced at the commencement of the coherer bridge construction process but proceeds in the form of ionization by collision, emanating from the field concentrated at the end of the bridging element. This is the breakdown visualised by Joffé and Von Hippel. It probably occurs when the insulating surface is very thick, and when a sufficiently great voltage is applied so rapidly that the somewhat slow coherer action can occur only slightly, if at all. It has been shown that about 0.003 of a second is required for complete coherer effect.

It is interesting to compare this discussion with ideas previously set down by Dr. Holm.[16] It was then noted that there are coherer actions corresponding to very large bridging resistances, of the order of a few thousand ohms. Holm did not believe at that time that the conditions thereby established were metallic, but this seems very probable in view of the coherer theory now outlined.

The large resistances appear feasible when due consideration is given to the extraordinarily restricted electron paths which exist in the thin metallic elements. It may be mentioned, for example, that an element 100Å in length, with a radius 10Å, and a specific resistance of about 20 times that of the pure metal, has a resistance of at least 1000 ohms, according to the kind of metal.

Burstyn[17] has made the interesting suggestion that the film between two contacts may actually be compressed, and consequently undergo physical change, on account of electrostatic attraction between the respective contacts. It will be realised that when contact surfaces come very close together without actually conducting current there may be considerable electrostatic attraction between them, according to their size and shape and the potential difference. In the case where two plane contacts are separated by a thin layer of non-conducting or poorly conducting material the conditions are conducive to high forces of attraction, and if the film substance is mechanically weak it may be appreciably deformed. Burstyn makes use of the following formula giving the force

[16] "Über metallische Kontaktwiderstände," *Wiss. Veröff. aus dem Siemens-Konzern*, 7, Heft 2, 1929, § 14.

[17] "Elektrische Kontakte," Berlin (Springer), 1937, p. 56.

of attraction between two parallel surfaces having an area A(cm.^{2}) and separated by a distance d(cm.). If V is the potential difference between the plates, the attraction is

$$F = \frac{A}{8\pi d^2} \times \frac{V^2}{9 \times 10^4} \text{ dynes} \qquad (20)$$

or

$$.45 \times 10^{-9} \frac{A V^2}{d^2} \text{ grams.} \qquad (21)$$

If the thickness of the film is taken as 10^{-6} cm., the force corresponding to a contact potential of 1 volt is approximately 100 grams per square centimetre, representing a high specific pressure at the points of actual contact at the interface.

The same problem has been discussed by Holm in a slightly different way. He commences with formulae equivalent to (20) and (21), and regards A as the Hertz-surface, d being representative of the average thickness of the insulating film (averaged quadratically) at those points of the surface which do not make metallic contact. For a Hertz-surface well filled with contact points Holm takes the following values as representative of his experimental results:

$A = P \times 10^{-6}$ (where P is the contact pressure),
$V < 0.20$,
$d > 5 \times 10^{-8}$.

Substitution of these values in equation (21) gives the attraction between the contacts as $0.0072P$, which may be regarded as an entirely negligible increase of pressure.

Different conditions may arise with accurately ground plane contacts where comparatively large insulating surfaces exist between a small number of actual contact points. In this case it is only permissible to take d as larger than 10^{-6}, so that if V is 0.20 as previously, substitution in equation (21) yields a value of 18 grams per square centimetre for the force of electrostatic attraction.

These examples serve to indicate the magnitude of the forces which may be experienced due to electrostatic attraction between the contacts. It will be understood that the force in a given case is considerably influenced by the thick-

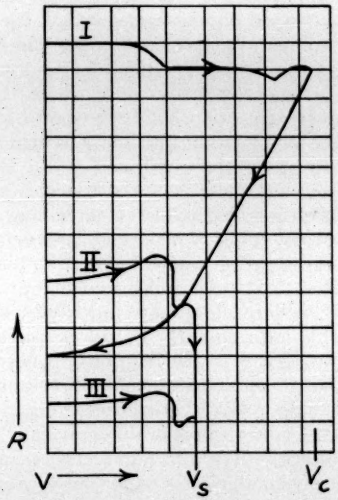
ness of the intervening film, and in view of the fact that this is difficult to determine accurately, it is generally possible to estimate the attraction only between fairly wide limits. In most practical cases, the attraction is quite negligible in relation to normal contact pressures. It may, however, become important in experiments carried out with low pressures unless the contact areas are so small that no appreciable attractive force can exist. In any case, it is necessary to realise the possibility of electrostatic forces being developed in addition to the applied contact pressure, so that due allowance may be made in cases where the conditions are such that these forces are appreciable.

The modern theory of coherer action, as represented by the researches of Holm and his collaborators, may be summed up as follows:

The occurrence of coherer action is accompanied by the building up of metallic bridging particles or filaments through the film at the interface between the contacts. The resistance of the interconnection thus established between the contacts is a reversible function of the voltage applied to the contacts, and is represented by a curve of the form shown in Fig. 3. The filaments are normally a few tenths of μ in thickness, but the process of their evolution is not thoroughly understood at present. It is possible that in the early stages free ions and later in the process fluid metal contribute to the structure. Upon the occurrence of coherer action the voltage falls directly to something less than V_s, the voltage at which contacts free from surface films are melted permanently together, so as to present an irreversible characteristic. It will be seen from the curve that the resistance commences at a high value, and that with increasing voltage the resistance shows small changes until the critical "coherer voltage" V_c is reached. The subsequent coherer action is characterised by a sudden fall of voltage, as indicated by the straight part of the curve, and if this voltage is still further reduced, e.g. by means of a resistance, the complete reversible characteristic is obtained. For the purpose of illustration, two curves have been added, corresponding to metals free from surface films and operating at high and low contact pressure respectively. During the first part of each curve, the resistance increases slightly, prob-

ably on account of increased temperature of the contacts due to joulian heating. A point is eventually reached where the resistance begins to fall; slowly at first and then more rapidly until finally there is an immediate fall to a value considerably

FIG. 3.



Resistance-voltage characteristics of contacts with and without surface films. I. Reversible characteristic of coherer effect on contacts with surface film; II. Irreversible characteristic of pure metallic contacts at low pressure; III. Irreversible characteristic of pure metallic contacts at high pressure. V_s is critical melting voltage at which contacts coalesce; V_c is critical voltage at which coherer action commences.

below the initial resistance. This effect is attributed to physical change in the hardness of the respective contact metals under the effects of heating, so that the effective area of the contact regions is increased and a lower contact resistance results. Further increase of applied voltage produces a tendency for the resistance to increase once more, but a point is soon reached, corresponding to the voltage V_s, where the contact surfaces weld together. The characteristic in this case is seen to be an irreversible one.

EXPERIMENTAL RESEARCHES.

Experiments dealing with coherer action were carried out by numerous investigators over an extensive period dating from the time when the phenomenon was first observed. Experimental and theoretical work was stimulated by the development of coherers for telephone work in the early days of electrical communications, and a vast amount of experimental data has been obtained on various aspects of the subject. It is only during comparatively recent years, however, that the basic fundamentals of coherer action and associated phenomena have been effectively probed. Much of the recent development in this connection has been due to refinements in the technique of observation and measurement, but a considerable part must also be attributed to the extension and unification of physical theories. The conceptions of modern physics have been found capable of explaining some of the experimental observations which had previously provided room for much speculation and difference of opinion.

The researches of Holm [18] and his collaborators are representative of the modern viewpoint, and have yielded instructive and valuable information. In the course of this work, consideration was given to the relationship between type of contact, thickness of surface film, contact pressure, and direction of current flow. Observations were also made on the difference in behaviour of films of different age.

The effect of age is shown in Fig. 4, where coherer voltage is plotted against film thickness expressed in Ängstrom units (10^{-8} cm.). It is seen that there is a very close approximation to perfectly linear relationship between V and the film thickness for both old and new films, so that the voltage which produces coherer action is directly proportional to the film thickness. It is found from the curves that the coherer voltages for old and new films are respectively

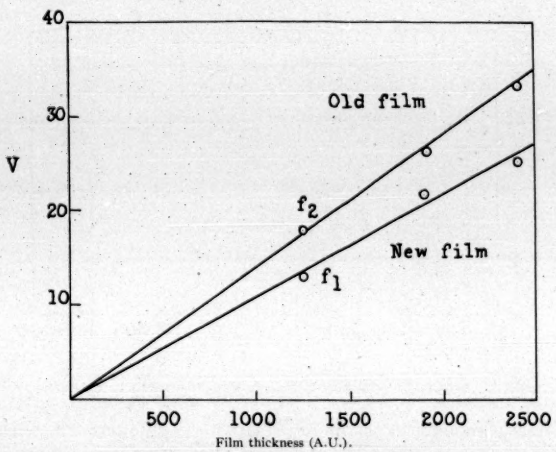
$$f_2 = 1.42 \times 10^6 \text{ volts per cm.},$$
$$f_1 = 1.10 \times 10^6 \text{ volts per cm.}$$

Experiments with alternating voltages at from 500 to 10^5 cycles showed that the effective value of the coherer voltage

[18] R. Holm and others, *Wiss. Veröff. a.d. Siemens-Konzern*, 10, 1931, pp. 1, 20.

was practically the same as in the experiments using direct current. On 50 cycles, however, the effective voltage was found to be too small by a factor of about 2 when compared to

FIG. 4.



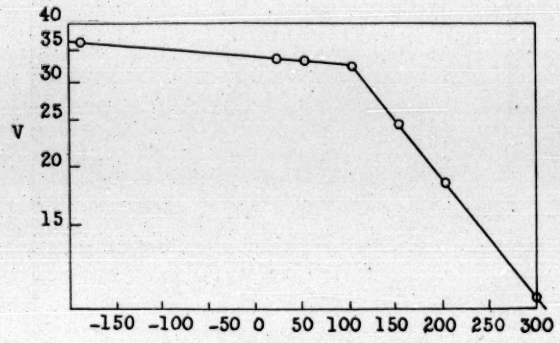
Relation between coherer voltage and film thickness.

the D.C. experiments. This discrepancy is explained by the fact that the time lag of the coherer effect, when taken as about .003 second, is of an order of magnitude which would allow crest voltages exceeding the effective voltage to be more effective than they would, for example, at 500 cycles, where the time between successive voltage maxima is 0.001 second.

Determinations of coherer voltage with respect to temperature are represented by Fig. 5. In this case the film thickness was 1250 A.U., and the measurements were made in vacuo so as to prevent increase of the oxide film thickness with increase of temperature. It will be noted that over the temperature range between -200 and $+100°$ C. there is only a slight fall of coherer voltage with increasing temperature, whereas for higher temperatures the fall is rapid. During these experiments it was found, incidentally, that higher

voltages were required for the coherer effect in vacuo than in air. A film which before and after the vacuum tests gave coherer action at about 16 volts required approximately 34 volts in vacuo.

FIG. 5.



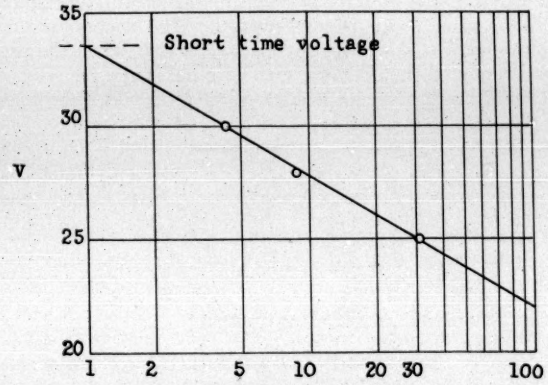
Relation between coherer voltage and temperature (Film 1250 A.U. in vacuo).

The foregoing experiments relate to conditions where the coherer voltage acts within a short time after its application (kurzfristige Fritterspannung). The coherer effect can in general be produced by lower voltages when they are allowed to operate for a longer time; several minutes, for example. Tests were carried out on a given contact by applying successively lower voltages and observing the time required for occurrence of the coherer effect in each case. It was found that with a contact requiring about 34 volts to produce the effect in a short time, the same effect could be produced by the application of 28 volts for 9 seconds, or 25 volts for 30 seconds, etc. The relationship between coherer voltage and the time of application of this voltage is shown in Fig. 6, from which it will be seen that, over the range of time considered, the fall of voltage is proportional to log t.

In a further set of experiments, the effects of circuit resistance were examined. In this case very high resistances were employed, and the voltage measurements were made with

an electrometer, in order to avoid disturbances produced by meter resistances. With a contact resistance of approximately 10^8 ohms, a normal coherer effect was obtained at 9

FIG. 6.



Relation between coherer voltage and time of application.

volts with a circuit resistance of 4×10^6 ohms. When this resistance was increased to 2×10^8 ohms it was found impossible to produce the effect. It is concluded from the experiments that if a constant interface resistance due to the presence of a surface film at normal room-temperature will permit the passage of a current I upon application of the coherer voltage, this effect will take place only if the circuit arrangement is such that a current $10\,I$ can flow, when the working e.m.f. is equal to the coherer voltage.

EFFECTS OF CONTACT PRESSURE.

We have already seen that the contact resistance between two bodies is dependent upon the area of the surfaces of actual contact. Determination of the relationship between these surfaces and the contact pressure is of fundamental importance in the theory of electrical contacts, and has consequently re-

ceived a considerable amount of attention from the experimental and theoretical viewpoints.

Certain special cases of elastic contact between solid bodies have been examined from the purely mechanical point of view notably by Heinrich Hertz, who developed formulae from which the area of contact between bodies of different shapes under pressure could be determined. The theory assumes that the bodies are completely elastic, so that when the pressure is removed they resume their original shape.

One of the problems considered by Hertz was that of contact between two spheres. The original formulæ have been simplified by H. Bochmann,[19] who showed that if D_1 and D_2 are the diameters of the respective spheres or cylinders, the diameter of contact for a given pressure P between the bodies is given by

$$d = 32.506 \times 10^{-3} \sqrt[3]{\frac{PD_1D_2}{D_1 + D_2}}. \tag{22}$$

If both spheres are of the same diameter,

$$d = 25.8 \times 10^{-3} \sqrt[3]{PD}. \tag{23}$$

In the case of cylinders engaging crosswise,

$$d = \mu 40.955 \times 10^{-3} \sqrt[3]{\frac{PD_1D_2}{D_1 + D_2}}, \tag{24}$$

where μ is a function of an angle whose magnitude is dependent upon the curvature of the cylinders. If both cylinders are of the same diameter,

$$d = 32.506 \times 10^{-3} \sqrt[3]{PD}. \tag{25}$$

According to the researches of Bochmann, a correction factor of approximately -10 per cent. is to be applied to the numerical terms in these formulæ. It will be seen that in all cases the relation between diameter of contact area, pressure and diameter of the contact bodies is given by

$$d = k \sqrt[3]{PD}, \tag{26}$$

[19] "Die Abplattung von Stahlkugeln und Zylindern durch den Messdruck," Dissertation, Dresden, 1927.

while for the area of contact we have

$$s = k.(PD)^{\frac{1}{3}}. \tag{27}$$

It follows that the specific pressure, P/s, can be expressed by the alternative equations

$$p = kP/\sqrt[3]{P^2D^2}, \tag{28}$$

$$p = k\sqrt[3]{P/D^2}. \tag{29}$$

It will be observed from equations (27) and (29) that the area of contact varies in accordance with $\sqrt[3]{P^2}$, whereas the specific pressure is proportional to $\sqrt[3]{P}$.

According to the measurements of Stribeck,[20] the formulæ developed by Hertz are also valid in the case of inelastic deformation of the bodies. It was found that in the case of very high pressures, when cold flow has taken place, the specific pressure p varies more slowly than in direct proportion to $\sqrt[3]{P}$ in the case of two spheres or a sphere and plate. Finally, p approximates to a constant value, and the area of contact varies proportionally with the pressure.

RESEARCHES OF E. CONTIUS.

The subject of inelastic deformations of bodies of various shapes under pressure has been dealt with very fully by Dr. Eberhard Contius in his dissertation on the influence of the magnitude of pressure and surface upon contact resistance, published at Dresden in 1929. The object of this work was to examine theoretically and experimentally the conditions attending the deformation of bodies in contact with each other under pressure and thus to determine the laws governing the relationship between surface condition, shape, pressure and contact resistance.

In one set of experiments, the area of contact produced between two copper cylinders placed crosswise was determined for various applied pressures by means of a Brinell microscope. By plotting this area against the applied pressure it was found that a straight-line relationship was obtained, showing that $s = k.P$. Measurement from the curves

[20] *Zeits. des V D I*, 1907, pp. 1445 et seqq.

showed that in this particular case, $k = 0.0113$ approximately, when s was expressed in mm.^{2} and P in kg.

Further experiments were made with copper contacts of different shapes bearing upon a polished steel plate. It was found that in all cases the area of contact was equal to kP, and k had a value ranging between 0.0113 and 0.0118.

Contius here makes reference to a formula developed by Binder in which the contact resistance is expressed by $R = 1/2\lambda a$. This formula can be obtained from equation (13), giving $n\pi f = P/a^2$, and substituting in equation (16). We have just seen that $s = kP$, so that substituting $k = 0.0113$ we have

$$s = \pi a^2 = .0113\, P.$$

In cm. units this becomes

$$s = .000113\, P,$$

so that we have

$$a^2 = .000113\, P/\pi$$

and

$$a = .006\sqrt{P}. \qquad (30)$$

If the conductivity λ is taken as $1/1.8 = .555$ for copper, we have by substitution

$$R(\text{ohms}) = \frac{1}{10^6 \times 2 \times .555 \times .006\sqrt{P}}.$$

This reduces to

$$R = \frac{1}{6660\sqrt{P}}$$

or

$$R = .00015/\sqrt{P}, \qquad (31)$$

so that the constant in the resistance formula is equal to 0.00015.

On the basis of the foregoing formulæ, and after detailed investigation of the types of deformation produced in contact surfaces of various shapes by the application of pressure Contius arrived at the results listed in Table I which shows

TABLE I.

Relation Between Contact Resistance and Pressure (E. Contius).

Type of Contact.	Conditions.	Values of n and k in Resistance Formula $R = k/P^n$.	
		n.	k.
Point–point	Theoretical	1/2	0.000204
Point–point	Empirical	1/2	0.000230
Cylinders crosswise	Theoretical	1/2	0.000150
Cylinders crosswise	Empirical	1/2	0.000205
Contact finger (line contact)	—	2/3	0.000330
Plane, 1.6 cm.^{2}	Normal finish	1	0.000430
Plane, 1.6 cm.^{2}	Normal finish, and lubricated	1	0.000340
Plane, 1.6 cm.^{2}	Tinned	1	0.001250
Plane, 3.2 cm.^{2}	Ground, new	2	0.400000
Plane, 1.6 cm.^{2}	Ground, new	2	0.050000
Plane, 0.8 cm.^{2}	Ground, new	2	0.01000
Plane, 1.6 cm.^{2}	Ground, much used	5/3	0.001900
Plane, 1.6 cm.^{2}	Ground, lubricated	4/3	0.002800
Plane, —	Ground, oxidised	3/4	0.001700

the wide variation in the contact resistance properties of the different types of contact.

A series of curves representing some of the results obtained by Contius are given in Fig. 7. These curves are very instructive in showing the characteristics of the different types of contact, and the rate at which the contact resistance decreases in each case with increase of pressure.

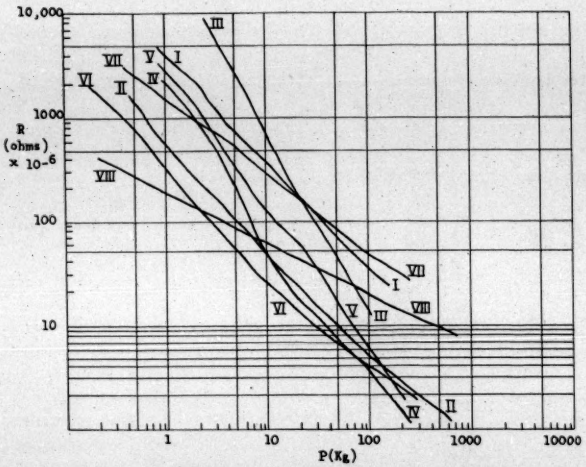
It will be noticed that flat contact surfaces show a steep characteristic in this respect, owing to the relatively rapid increase in the number of contact points as the pressure is raised. This property of surface contacts has been remarked upon by several investigators, and is satisfactorily explained by the analysis of contact phenomena between plane surfaces which has already been given.

From the curves it will be observed that with a pressure of 1 kg. the lowest contact resistance is given by point contacts, as represented by curve VIII, and that the resistance of normally finished surfaces is considerably lower than that obtained with smoothly ground surfaces, as represented by curves III, IV, V and VII. With a pressure of 10 kg., the difference between the respective contacts is not so marked,

but there is still a general preference for normal surfaces as compared with ground ones.

For pressures exceeding 100 kg. it will be noticed that pointed contacts, as represented by curves I and VIII, should

FIG. 7.



I. Cylinders placed crosswise. II. Plane surfaces, normal finish, no oxide, 0.8 to 3.2 c.m.². III. Plane surfaces, ground finish, no oxide, 1.6 c.m.² (new). IV. Same as III, but used several times. V. Same as III, but lubricated. VI. Plane surfaces, normal finish, no oxide, 1.6 c.m.², lubricated. VII. Plane surfaces, ground finish, oxidised, 1.6 c.m.². VIII. Pointed contacts.

be avoided, and that the best results are represented by curve IV, corresponding to a surface considerably used after initially being ground smooth. The normally finished surfaces do not give such good results at these high pressures, but there is little to choose between the different kinds of finish on flat surfaces, provided that they are free from oxide. The very poor performance of a flat oxidised surface, as represented by curve VII, is particularly noticeable, and emphasises the importance of freedom from oxide if low contact resistance is to be obtained.

The conclusions arrived at by Contius may briefly be

summarised as follows, and represent a valuable contribution to quantitative information on the general properties of contact under pressure:

1. In the case of pointed copper contacts the area of contact increases in proportion to the pressure when the load exceeds the yield point of the material. In the equation $s = kP$ the constant k depends upon the shape of the bodies.

2. In the case of pointed contacts the pressure and resistance are related in accordance with the formula $R = k/\sqrt{P}$. The actual or effective contact surface approximates closely to the apparent surface.

3. Contact between plane surfaces is formed by the aggregate of several points of contact, the number and size of which depend upon the applied pressure and the surface condition. Pressure and resistance are related by the formula $R = k/P^n$, where the exponent n depends upon the nature of the surfaces. In the case of accurately ground and polished surfaces, $n = 2$. With increasing pressure approaching the yield point of the entire contact the value of n changes gradually to $\frac{1}{2}$.

4. Particularly smooth surfaces are characterised by high contact resistance. If however, the surfaces are very rough, the conditions become similar to those of pointed contacts.

5. In the case of ground and smooth surfaces the contacts of large area have a higher resistance than the smaller ones. In the case of normally finished surfaces there is no appreciable difference in this respect.

CONTACT VOLTAGE CHARACTERISTICS.

We have already mentioned the behaviour of contacts with and without surface films when the applied potential is varied. It will be understood that the behaviour of contacts under these conditions is of considerable practical importance. The conditions have received detailed consideration, notably by Holm and his collaborators, and it has been found possible to formulate satisfactory theories to account for the observed phenomena.

The general effect of an increase of contact voltage is an increase of current through the interface which in turn gives rise to an increase in the temperature of the actual points of contact. The final result is twofold:

1. The specific resistance of the contact material changes, being increased in the case of materials with a positive temperature coefficient and decreased in the case of a negative coefficient.

2. The contact material becomes softer, especially in the case of high temperatures, so that with a given mechanical pressure the respective contact surfaces make more intimate contact, and the electrical contact resistance is consequently reduced.

The general tendencies of these two effects are seen to be mutually opposed, and it is important to know their respective influence upon the contact resistance when the contact voltage is progressively increased. If the contact resistance behaved as a purely ohmic resistance obeying Ohm's law its value at any temperature t would be $R = R_0 (1 + \alpha t)$, where R is the resistance at the elevated temperature T, R_0 is the resistance at temperature T_0 and $t = T - T_0$. A curve connecting resistance with applied voltage in this case would show a continued increase of resistance with increase of voltage. In the case of a contact, however, the conditions are very different.

It has been found [21] that in the case of pure metallic contacts free from surface films there is a very simple relationship between the contact resistance R, the temperature t of the actual contact surface and the contact voltage V, provided that the contact surface remains constant. The derivation of the relationship is based on work by Kohlrausch, Diesselhorst and Meissner [22] on the theory of heat conduction, and the following formulæ represent approximations:

$$t = V^2/8\gamma P, \tag{32}$$

$$R = R_0 (1 + \tfrac{2}{3}\alpha t) \tag{33}$$

where γ is the thermal conductivity of the metal and P its specific resistance. It follows that for every value of V there is a definite temperature t in the contact, irrespective of the size and form of the contact surface. Since this temperature

[21] R. Holm, "Über elektrische Kontakte," *E. T. Z.*, 1935, p. 537.

[22] References are given in the *Wiss. Veröff. aus dem Siemens-Konzern*, 9, 1930, p. 300.

cannot be increased beyond the melting point of the metal without collapse of the interface and welding of the contacts there is a limiting critical value of V, which is represented in Fig. 3 by V_s. For metals, this voltage has an order of magnitude ranging between 0.2 and 1 volt, whereas for carbon the value is about 2.5 volts.

Even the purest contact metals when used in air acquire a film which may be only monomolecular in thickness but is attached so strongly to the metal that it can rarely be removed by rubbing without affecting the parent metal. Under ordinary contact pressures, however, the specific pressure per unit of actual contact area is adequate to prevent extensive departure from the conditions we have just mentioned. It is only the films (chiefly oxides) which form on base matels, and which may range in thickness from about 20 to several thousands of atomic layers, which cause these conditions to become radically changed. In this case the $R-V$ characteristic is of the form represented by curve I in Fig. 3, which has already been discussed.

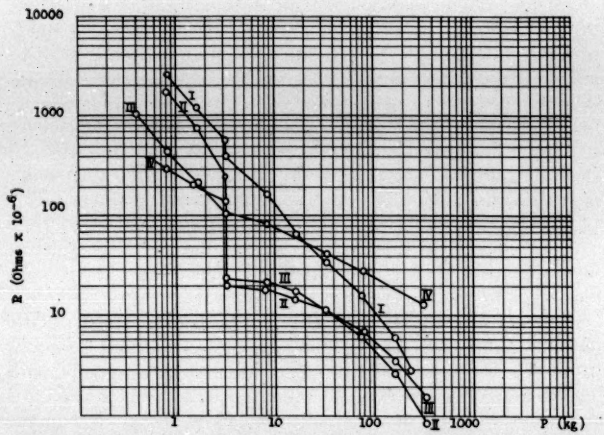
Curves II and III represent the characteristics of pure metallic contacts. These curves conform initially to equation (33) and thus show a uniform increase of resistance with increase of contact voltage. This characteristic persists until a certain voltage is reached, corresponding to a contact temperature which brings about softening of the contact metal, so that more regions of metallic contact are produced. This causes a reduction of contact resistance, which is gradual at first and then very abrupt, reducing the contact resistance to about half its initial value. Further increase of contact voltage causes a corresponding increase of resistance, substantially in accordance with equation (33) until finally the limiting voltage V_s is arrived at, when the contact surfaces coalesce. It will be noticed that the general properties of the $R - V$ curves and the critical voltage V_s are independent of the contact pressure. Extensive investigation of the resistance characteristics of various metals has been made by Holm and his collaborators.[23]

The effect of current variation upon contact resistance

[23] R. Holm and others, *Wiss. Veröff. a.d. Siemens-Konzern*, 7, 1929, pp. 217, 272; 10, 1931, pp. 1, 20.

was examined experimentally by Contius, who found the same effects of contact heating while using a different method of investigation. The results obtained by Contius on several forms of contact are given in Fig. 8. At a given arbitrary

FIG. 8.



Influence of current increase on contact resistance (copper contacts). I. Plane, 1.6 cm.², polished, oxidised; II. Plane, 1.6 cm.², polished, oxide-free; III. Plane, 1.6 cm.², rough, oxide-free; IV. Cylinders, crosswise.

contact pressure of approximately 3.15 kg. the current flowing through the contacts was steadily increased until a stable condition was reached in which there was no further decrease in contact resistance. The measurements of resistance with increasing contact pressure were then continued with the original current value. The sudden fall of contact resistance due to the heating effects of the current is very evident in these curves, which show also the very different behaviour of the different contact forms.

The least variation of resistance is given by the point-contact between crossed cylinders, which would be expected from the theoretical consideration that such a contact surface may be regarded as complete, and that no substantial increase of

contact area would occur under the described conditions of test. Smooth plane oxidised surfaces also show only a small drop in resistance with increased current. This feature might be accounted for by the fact that the collapse of the metal at the actual points of contact results in the establishment of relatively few additional points of contact, owing to the presence of the oxide film. These conditions do not apply to unoxidised surfaces, as will be seen from the corresponding curves, which show considerable decrease of resistance, indicating a substantial improvement in contact, when the current is increased.

CONCLUSION.

It is seen that the subject of electrical contact resistance is of great importance to the engineer, and also presents several problems of interest to the physicist. Although these problems have received considerable attention, there is as yet no thorough coördination of the results, and much work remains to be done before this end can be achieved. It is hoped that the present article may serve to give a true perspective of the subject, as well as an indication of those branches which offer scope for further research.

RIDGEWAY CLOSE,
OXSHOTT, SURVEY,
ENGLAND.

Eye Protection from Glare and Injurious Light.—(*Public Utilities Fortnightly*, Vol. XXVI, No. 13.) Welders and men employed on certain furnace and foundry operations should have eye protection that not only safeguards their eyes from the glare of visible light but also from dangerous infra-red and ultra-violet rays radiated by the flame and the molten metal, according to H. R. MOULTON, assistant research director of the American Optical Co., Southbridge, Massachusetts. For example, he states, an instant's exposure to an arc welding operation at close range may result in a "flash" and cause several days' lay off with extremely sore eyes. Repeated exposure may cause permanent damage to the eyes. It has been adequately demonstrated, according to the scientist, that the invisible ultra-violet and infra-red rays do not aid vision but actually are a dead load which does no good. And under certain conditions these rays may do real harm. Eyesight specialists know that ignorance of the dangers of these invisible rays may lead to disastrous results, a point not fully realized by some industrial managers. After long research, scientists finally developed absorptive glasses which represent a notable contribution to eye safety. It should be pointed out that the protection provided against the invisible rays depends on the chemical content of the glass, not its color. Among the absorptive glasses developed in the laboratories of the American Optical Co. is one that is chemically compounded to stop 98 per cent. or more of the invisible rays. Every melt of this glass is carefully tested for its absorptive properties and its conformance with the U. S. Bureau of Standards recommendations and with all state requirements for welding glass. This noviweld glass effectively prevents the annoying feeling of hot sand in the eyes and keeps them cool and comfortable. Another absorptive glass of scientific interest is a hardened cobar glass which in addition resists the impact of flying particles. This quality is due to a special toughening process.

R. H. O.

NOTES FROM THE NATIONAL BUREAU OF STANDARDS.*

SPECTROPHOTOMETRIC DETERMINATION OF PRASEODYMIUM, NEODYMIUM, AND SAMARIUM.

Attempts to analyze materials composed essentially of the rare earth elements have not been particularly successful because these elements are so nearly identical in their chemical and their physical properties. Many of the rare earth elements, however, form salts which give rise to characteristic absorption bands when their solutions are observed by means of a spectroscope. As reported in the *Journal of Research* for June (RP1395), Clement J. Rodden has taken advantage of this property to determine these elements without separating them chemically.

Three of the rare earths which form colored solutions, praseodymium, neodymium, and samarium, can be determined with a fair degree of accuracy by measuring the transmittancy of light through their solutions.

By determining the relation between the spectral transmittancy and concentration of essentially pure salts of praseodymium, of neodymium, and of samarium, curves have been constructed by means of which mixtures of these three elements have been analyzed. In addition, the effect of other rare earth elements, particularly lanthanum, in the determination of each of the three elements in question, as well as the effect of each of the three on the others, were ascertained, so that appropriate corrections can be applied.

The region of the spectrum studied ranged from 350 mμ to 1000 mμ. Spectral transmittancy curves for lanthanum, cerium, praseodymium, neodymium, samarium, europium, and gadolinium were obtained by means of a photoelectric spectrophotometer. The absorption band found to be most suitable for the determination of praseodymium was at 446 mμ, for neodymium the bands at 521 mμ and 798 mμ, and for samarium, 402 mμ.

* Communicated by the Director.

A suggested procedure is indicated for the analysis of mixtures of the cerium group of rare earths, obtained by precipitation of their double sulfates in the course of a mineral analysis.

DETERMINATION OF CARBON MONOXIDE.

Joseph R. Branham, Martin Shepherd, and Shuford Schuhmann of the Bureau's Chemistry Division are investigating the accuracy and reproducibility of existing methods of gas analysis. One of the papers reporting results of this investigation will be published as RP1396 in the *Journal of Research* for June. In this work, carbon monoxide of known purity was analyzed by the slow-combustion method. The contraction after burning, the carbon dioxide produced, and the oxygen consumed were measured. Apparatus with and without rubber connections were used. The distinct effect of the amount of liquid water present within the combustion pipette and burette was measured. Analyses were performed with all the gases dry, as well as saturated with respect to water vapor. The stoichiometric relationship representing ideal physical and chemical conditions is $2\,CO + O_2 \rightarrow 2\,CO_2 + TC$ (where TC = total contraction after burning); the observed relationship representing average laboratory practice by the customary method and apparatus was $2\,CO + 1.001\,O_2 \rightarrow 1.986\,CO_2 + 1.014\,TC$. The purity of the sample, expressed as per cent. by volume, was known to be better than 99.99. The purity determined by analysis varied from 99.13 to 101.74, depending upon the measurement selected for calculation. Best results were obtained by computing CO from $TC + CO_2$; the purity so indicated was 100.01 ± 0.04. The departure from the stoichiometric relationships were all accounted for experimentally and theoretically.

DETERMINATION OF FREEZING POINTS.

In RP1397 by Beveridge J. Mair, A. R. Glasgow, Jr., and Frederick. D. Rossini, which will be published in the *Journal of Research* for June, simple time-temperature freezing and melting curves are analyzed, and a procedure is outlined for

determining from them the freezing point of a given substance and the amount of impurity in it. The procedure was applied to a number of different known solutions of hydrocarbons ranging from 0.006 to 0.115 mole fraction in concentration of solute. For the systems examined, it was found that the values for the freezing point of a given substance obtained from both freezing and melting curves were always in accord within their respective limits of uncertainty, and that the estimated amount of impurity was in error by not more than about 10 per cent. of itself, on the average.

MATERIALS IN SOIL CORROSION TESTS.

Many lines of industry including petroleum refining, railway transportation, chemical manufacture, etc., have been confronted with serious corrosion problems. By careful selection of alloys developed to resist corrosion under specific environmental conditions, the life of equipment in these and other industries has been considerably prolonged. Since many of these materials have been shown to be resistant to sea and other natural waters, dilute acid and alkaline solutions, organic acids, sulfur compounds, reducing environments, or to other factors or conditions characteristic of corrosive soils, it is important to determine the suitability of these materials for service underground.

At several times beginning in 1922 specimens of corrosion-resistant ferrous and nonferrous metals and alloys, metallic and nonmetallic coatings, and miscellaneous materials were buried at a number of test sites located in soils in which the corrosive factors differed widely in nature and intensity. A series of progress reports on this investigation has been prepared, but in no single report can a description be found of all of the materials which are under test or for which corrosion data are available. In order that metallurgists, corrosion engineers, and others concerned with the behavior of metals underground may have available in convenient form a list of the materials which have been included in the investigation, a description of all such materials of general interest has been prepared by I. A. Denison of the Underground Corrosion Section for distribution as Letter Circular LC646, entitled "Ma-

terials in the National Bureau of Standards Soil-Corrosion Tests." The significant features of the various materials are discussed from the standpoint of their resistance to corrosion in soils and in other environments in which the same corrosive factors are present. The specific contributlon of the various alloying elements to corrosion resistance is discussed for the different types of materials.

WEARING QUALITY OF CURRENCY PAPERS.

Replacing worn out paper currency costs the Federal Government several million dollars each year. Research at the Bureau, in coöperation with the Bureau of Engraving and Printing, has resulted in improvement of the quality of currency paper, but at the same time conditions of use have grown more severe. The problem, therefore, continues to be important. To tell whether or not a change in the paper is actually an improvement is something of a problem in itself, because service tests of paper currency in circulation require much time, and it is difficult to get adequate returns on comparable treatments. Hence, a quick laboratory wear test that will simulate the kind of treatment that paper currency gets in circulation is much needed.

F. T. Carson and V. Worthington of the Bureau's Paper Section have recently developed a wear test that meets this need. It is particularly adapted to determining the relative wearing quality of a given type of paper that has been treated in various ways to improve its performance. The test is made in two stages. First, a square of the paper is crumpled to a certain volume by means of a piston working in a cylinder. Then mechanical fingers straighten and smooth the paper, and a mechanism rolls the paper up and puts it back in the cylinder where it is again crumpled. This is repeated many times until the paper looks and feels very much like paper currency that has been in circulation for several months, although the artificial wearing-out process requires only a few minutes. The whole process is completely automatic and at the end of a specified amount of treatment the crumpling apparatus stops. In the second stage of the test the amount of damage that has resulted from the crumpling treatment is determined.

Strength and stiffness are sometimes measured, but the most valuable criterion has been found to be the change in the rate at which air will flow through the paper under a given pressure. This shows how much the structure has been opened up, which is closely related to the roughness or fuzziness of the surface, its ability to catch dirt and absorb oil and grease, and the probability of impairment of printed images and characters on the paper, as well as the change in strength and stiffness. This second stage in the test is accomplished chiefly by means of a new permeameter developed by F. T. Carson especially for this work.

These instruments have been very helpful in predicting quickly the probable improvement to be expected from a given change in the paper used for paper currency. The standardization and improvement of these instruments is being continued and the method for determining the relative wearing quality of currency-type papers is constantly being improved.

The complete account of this work will be published as RP1390 in the June number of the *Journal of Research*.

Chronoscope.—Split seconds that are ages to a bullet or a camera shutter are measured as easily as a wrist watch measures the time of day be a new device called a chronoscope, developed by the Research Division of the Remington Arms Company. The device, built into a small portable cabinet, splits the second 1000 ways and will measure from one up to 200 of these milliseconds with less than one per cent. error. It has already proved valuable for studying the effect of velocity and flight time of bullets on accuracy, range, trajectory, and hitting power, but its use is not confined to ballistics. Many of the most important operations in science and industry are performed in much less time than is needed for the flick of an eyelash. Any of these can be clocked with the chronoscope providing only that an electrical impuse can be obtained at the beginning and end of the event. The maximum swing of an indicating needle across a scale tells the operator precisely how long it takes a fuse to blow out, a photoflash bulb to light up, a telephone relay switch to snap, or a blasting cap to go off. Experimental gunsmiths using the instrument can make velocity measurements heretofore possible only in well equipped ballistic laboratories. Projectile velocities can be measured accurately over distances as short as five or ten feet. "Remaining velocity" can be measured after the projectile has traveled some distance. The actual velocity at 100 or 500 yards, for instance, can be measured over ten feet. This has been impossible with the Boulenge chronograph, the standard device in all ballistic studies for measuring short time intervals. Such measurement has been very cumbersome by any other method. The chronoscope indicates the time interval from a quantity of electricity which passes through a specially designed galvanometer while the measured event is taking place. The galvanometer resembles a conventional portable indicating electric meter. A vacuum tube switching circuit starts the current at the beginning of the interval and stops it at the end. A photoelectric cell can be used to obtain the start and stop impulses. In ballistic studies, the conventional muzzle wire and target plate can be used. The single scale from which readings are taken really serves as five scales. These ranges are 10, 20, 50, 100 and 200 milliseconds.

R. H. O.

THE FRANKLIN INSTITUTE.

MEDAL DAY MEETING,
WEDNESDAY, MAY 21, 1941.

The annual Medal Day meeting was called to order at three-thirty o'clock P.M., by the President, Dr. Philip C. Staples.

The President announced that the minutes of the previous meeting had been printed in full in the May issue of the JOURNAL and that, if there were no objections, they would stand approved as printed.

The President then called upon the Secretary of the Institute, Dr. Henry Butler Allen. Dr. Allen reported that it was the custom to suspend the business reports for the Medal Day meeting and stated that the business of the day was the award of Medals.

Dr. Staples reminded the meeting that the Committee on Science and the Arts has been in existence for over one hundred years, and that its work embraces the searching of the fields of science and technology, to offer awards for scientific achievement.

He then outlined briefly the duties of the Committee and read from the annals of the Institute the names of many men who are famous today in various fields of Science and industry, who, in their earlier days, had received Medals from The Franklin Institute. He stated that the encouragement given to men through these awards was a service the Institute rendered to science, following the purpose for which it was founded, "the promotion of the mechanic arts and the dissemination of scientific knowledge."

The presentation of honors then became the order of the day and the following awards were made.

	Sponsors
Presentation of Certificate of Merit CHARLES WILLIAM AKERS, President, Breeko Corporation, Nashville, Tennessee.	Mr. Samuel Shoemaker
Presentation of Longstreth Medal BENJAMIN JAMES WILSON, Chief, Mechanical Division, Research Department, Leeds and Northrup Company, Philadelphia, Pennsylvania.	Dr. James Barnes
Presentation of Wetherill Medal HAROLD STEPHEN BLACK, Bell Telephone Laboratories, Incorporated, New York City.	Dr. W. R. Wright

Presentation of Brown Medal WILLIS HAVILAND CARRIER, D.Eng., Chairman of the Board, Carrier Corporation, Syracuse, New York.	Professor C. M. Gay
Presentation of Clark Medal RAYMOND MOWER CONNER, Director, Testing Laboratories, American Gas Association, Cleveland, Ohio.	Mr. W. H. Fulweiler
Presentation of Levy Medal JOHN MOYES LESSELLS, Associate Professor of Mechanical Engineering, Massachusetts Institute of Technology, and CHARLES WINTERS MACGREGOR, Ph.D., Associate Professor of Mechanical Engineering, Massachusetts Institute of Technology.	Dr. C. B. Bazzoni
Presentation of Potts Medal HAROLD EUGENE EDGERTON, D.Sc., Associate Professor of Electrical Engineering, Massachusetts Institute of Technology.	Mr. L. P. Tabor
Presentation of the Franklin Medal and Certificate of Honorary Membership SIR CHANDRASEKHARA VENKATA RAMAN, F.R.S., LL.D., D.Sc., Director, Indian Institute of Science, Bangalore, Mysore, India. Received by SIR GERALD CAMPBELL, K.C.M.G., D.C.L., LL.D., Envoy Extraordinary and Minister Plenipotentiary, The British Embassy, Washington, D. C.	Dr. T. D. Cope
Presentation of the Franklin Medal and Certificate of Honorary Membership EDWIN HOWARD ARMSTRONG, Sc.D., Professor of Electrical Engineering, Columbia University.	Dr. A. F. Murray
Presentation of Cresson Medal THE UNITED STATES NAVY, Received by the HONORABLE RALPH A. BARD, Assistant Secretary of the Navy, Washington, D. C.	Mr. F. H. Rogers

PAPERS.

"The Scattering of Light in Crystals"
by
SIR C. V. RAMAN
Read by Dr. T. D. Cope

"The New Radio Freedom"
by
DR. EDWIN H. ARMSTRONG

(A detailed statement, together with papers read at the meeting, will be published in an early issue of the JOURNAL.)

COMMITTEE ON SCIENCE AND THE ARTS.

(Abstract of Proceedings of Stated Meeting held Wednesday, May 14, 1941.)

HALL OF THE COMMITTEE,
PHILADELPHIA, MAY 14, 1941.

MR. COLEMAN SELLERS, 3RD, *in the Chair.*

The following report was presented for final action:

No. 3072: Work of Bernard Lyot in Study of Solar Corona.

This report recommended the award of a Howard N. Potts Medal to Bernard Lyot of the Meudon Obervatory, Paris, France, "In consideration of the first successful observations of the solar corona in the absence of a total eclipse."

JOHN FRAZER,
Secretary to Committee.

LIBRARY NOTES.

Photostat Service. Photostat prints of any material in the collections can be supplied on request. Orders received in the morning are filled the same day. The average cost for a print 9 × 14 inches is forty cents.

The library and reading room are open daily from nine o'clock A.M. until five o'clock P.M. Saturdays until 12 o'clock noon.

RECENT ADDITIONS.

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NOTES FROM THE BIOCHEMICAL RESEARCH FOUNDATION.

Systematic Qualitative Organic Microanalysis: Comparative Study of Procedures of Microextraction.—WILLIAM G. BATT AND HERBERT K. ALBER. (*Industrial and Engineering Chemistry, Analytical Edition*, **13**, 127, 1941.) Extraction procedures constitute an important step in the scheme of organic analysis on a micro scale. These procedures are of two types: the removal of an active ingredient from a heterogeneous mixture and the removal of undesirable material from an impure product. Separation of the active principle from a crude drug mixture is an example of the first type; the preparation of derivatives and their subsequent purification, an example of the second.

In control laboratories, where time is limited, methods which require less sample and consequently less extraction time are of distinct advantage, provided that the results are comparable to those obtained when using conventional apparatus.

Only methods for extraction of solid substances by heated solvents were investigated excluding liquid-liquid extraction processes. The merits of a standard macro-Soxhlet, a semi-micro-Soxhlet extractor and representative microextractors were compared.

Solvents were selected so that volatile and moderately volatile, low and high boiling, low and high surface tension menstrua were included. A solvent having special affinity for an extractable material likely to be present is preferable. The influence of atmospheric moisture on the solvent was reduced by using drying tubes on top of the condensers.

The range of boiling points of the solvents was between 35° and 100° C. at normal pressure. The boiling point in a completely enclosed extracting system, or one with a comparatively small condenser, may be slightly higher, especially in the case of a very volatile liquid. Decomposition of natural products when extracted with common solvents may occur if the boiling points, at atmospheric conditions, are high. These

dangers may be avoided by the application of reduced pressure in the extraction apparatus.

Salicylic acid and kieselguhr extracted with ether, anthracene and starch extracted with ether, and sodium chloride and aluminum oxide extracted with water, were the mixtures and solvents tested in comparing the macro- and semimicroextractors. Because of mechanical difficulties, salicylic acid mixed with sand and extracted with ether, caffeine and barium sulfate extracted with alcohol, and sodium chloride and sand extracted with water, were used for comparing the micro-

FIG. 1.

A *B* *C* *D*

Comparison of Methods of Evaporation.

A. Heating from underneath.
B. Heating from above, with Chromolox ring.
C. Spontaneous evaporation.
D. Heating from underneath but removing vapor phase by a jet of air.
(Courtesy *Industrial and Engineering Chemistry*.)

extractors. The salicylic acid-sand mixture was not used in the macroapparatus because of the great variation in bulk, which was appreciable but less noticeable when used in the smaller extractors. All the mixtures were tested in various ratios, so as to have the solid components approximately equal in weight, the soluble part in excess, and the insoluble portion in excess. The last mentioned would correspond to the extraction of material in which the percentage of soluble matter is

small (towards the lower limits of the weighing range of a microchemical balance).

A comparison of the methods of evaporation, with the usual one of heating from underneath, is presented in Figure 1; corresponding receiving flasks containing equal amounts of ether and of salicylic acid were used. The picture, taken with a polaroid screen to remove reflected high lights, illustrates clearly the advantages and disadvantages of the methods applied.

The condensation of solvent in the ground-glass joints of most of the extractors examined not only resulted in a direct loss, but was also a source of annoyance because of the suction formed when some of the solvent in the joints evaporated. To avoid winding all the glass joints, a generally applicable device was constructed.

The results obtained when using a semimicro-Soxhlet extractor show they are at least equivalent to those of the conventional macro-Soxhlet extractor. In addition, however, important advantages are offered by the use of the smaller apparatus: the period of extraction is shorter, up to two-thirds of the time for moderately soluble substances, although with a very soluble constituent mixed with an excess of inert matetial the time of complete extraction remains the same for both macro- and semimicroprocedures; less material is required; less space is occupied; no additional manipulations are introduced; and the initial cost is very favorable. These advantages justify the selection of the semimicro-Soxhlet extractor instead of the macroapparatus as the standard for comparison with the microapparatus.

The accuracy and precision of the determinations of the extract in the microextractors fall within the range calculated for the macro- and semimicro-Soxhlet extractors—i.e., $\pm$ 2.0 per cent. The advantages of the microextractors, even over the semimicroapparatus, may be summarized as: a shorter total extraction time, the possibility of using smaller amounts of material (limited only by the weighing accuracy of the available microbalance) and the comparative sturdiness of the apparatus. The less commonly used principle of percolation gives better service with respect to general applicability than siphoning (Soxhlet). Filter devices of metal permit the high-

est precision in weighing and maximum percentage of recovery of the residual matter without any contamination from the filtering material. The weighing of milligram amounts of residue on comparatively large filter paper surfaces (extraction thimbles) will not give reliable results, and the microanalyst has to face the fact that all extractors of the siphoning type using paper thimbles are limited to the determination of the extractable matter.

BOOK REVIEWS.

ATLAS OF NOMOGRAMS FOR PHYSICAL CHEMISTRY, by G. V. Vinogradov and A. I. Krasitlschikov. 144 pages, tables. 33 × 44 cms. Moskva. Government Publishing House of the Technical Literature. 1940.

This Atlas consists of 200 nomograms and is the first attempt ever made to systematize the application of nomography to the study of the problems of applied chemistry.

This Atlas is intended to simplify and to unify physico-chemical calculations thus allowing solutions to be reached much sooner.

The 144 page volume of instructions examines the principle of nomographic calculations and explains the use of nomograms.

B. d. B.

NEW HANDBOOK OF THE HEAVENS, by Hubert J. Bernhard, Dorothy A. Bennett, and Hugh S. Rice. 299 pages, illustrations, 16 × 24 cms. New York, McGraw-Hill Book Company, Inc. Price $2.50.

The authors were the editors of "Handbook of the Heavens," in which various chapters were written by various members of the Junior Astronomy Club in New York, but this new volume, which supersedes the other, has been completely written by Bernhard, Bennett, and Rice.

Intended for the beginner in astronomy (but not for the veriest youngster), it admirably accomplishes its purpose. The very abstruse topics are avoided completely, which is certainly better than trying to discuss a technical point in half-truths. Most of the material is directed toward those who will go out to look at the sky, and perhaps study it with field glasses or small telescopes. It is really a "handbook."

The slips are few and far between. Perhaps one should mention the repetition of the common error concerning our knowledge of the atmosphere of Mars. The Mount Wilson observers have determined that the instrumental technique employed would permit the detection in the atmosphere of Mars, of about 1/1000 as much oxygen as over an equal area of the Earth, and perhaps 5 per cent. as much water vapor; *none* is found, therefore these must be considered upper limits, and the lower limits may be zero. The authors have said, as usual, that these upper limits are the amounts that exist in the atmosphere of Mars.

We are told that the polar caps of Mars "may be either frozen carbon dioxid (sic) or frozen water." It has been known for some time that the polar caps nearly or entirely disappear in infra-red photographs, indicating that they are purely atmospheric phenomena, and not solid deposits on the planet itself.

There has been for the past fifty years an *average* of five comets per year, and not "sometimes as many as five."

But the book is very nearly free of errors and bad statements, and has a good glossary and index.

ROY K. MARSHALL.

CATALYSIS, INORGANIC AND ORGANIC, by Sophia Berkman, Jacque C. Morrell and Gustav Egloff. 1130 pages, illustrations, tables, 16 × 24 cms. New York, Reinhold Publishing Corporation, 1940. Price $18.00.

The production of high-octane motor fuels and lubricating oils through catalytic reaction and the foundation which has been laid for an improved petroleum industry are perhaps among the foremost reasons why attention is focused on the subject of catalysis. Although catalysis in both organic and inorganic reactions was recognized and studied for over a hundred years and many chemical processes and industries are based on catalysts, our knowledge of the phenomena is still largely uncoordinated. Of necessity to accomplish what has been accomplished, the properties of catalysts may be defined, the factors to be considered in describing the physico-chemical phenomenon are known, and acquaintance is had with the basis of the mechanism by which a catalyst functions. But there are many different viewpoints on the general theory of catalysis. It presents a challenge, the successful solution of which may contain untold promise.

The authors state in the preface "In order to arrive at an understanding of catalysis, it seemed logical in the present work to arrange the findings of the various workers in the field and their original interpretations into a systematic presentation of the subject with some consideration of its historic evolution. The book has been divided into chapters, each pertaining to a particular branch of the field significant in itself and at the same time related to the general subject of catalysis. This will permit the reader to acquire a knowledge of each specific branch of the subject and perhaps to visualize a logical thread running through the field of catalytic chemistry, thereby simplifying and facilitating a critical analysis of the available experimental facts." Accordingly, the book opens with a general treatment of the phenomenon of catalysis. An attempt is made to correlate the actions and effects of catalysts with their properties. Adsorption and catalysis are given special treatment and under this there is contact catalysis, differential and integral heats of adsorption and heats of activation. Following this there is taken up catalytic reactions taking place in heterogeneous and homogeneous systems.

The activity of a catalyst is very closely studied including methods of measuring catalytic activity. Statements on the activity and methods of preparation are given for a number of the metallic catalysts followed by activation and reactivation. Inhibitors in catalysis, promotors and poisons. as well as carriers in heterogeneous catalysis are taken up in order. There is explained how a catalyst may control a reaction, catalytic oxidation, hydration and dehydration, hydrogenation and dehydrogenation, halogenation, alkylation, condensation, concepts associated with polymerization, and catalytic isomerization. Chapter 9 deals with the functional factors affecting the physical character of a catalytic reaction —temperature, pressure, solvents.

For the purpose of a clearer presentation of experimental evidence of various catalytic reactions in organic and inorganic chemistry, the material is presented in the form of tables. They show the specific types of reactions which have been extensively studied and the physical conditions and type of catalysts which have been used to effect chemical changes in definite types of reactions and in compounds of definite molecular and atomic structure. The classification is with respect to type of reaction.

The last chapter of the book is devoted to catalysis in the petroleum industry. Catalysis here plays a major role. High octane motor fuels is given considerable space and there are also discussed synthetic motor fuels from coal, synthetic pure hydrocarbons and hydrocarbon products, and catalytic refining processes. It is shown that the developments in catalytic hydrocarbon chemistry and technology have prepared us not only for our future motor fuel requirements, but also for an ample and rapid development of a new synthetic organic chemical industry.

The magnitude of preparations and work in compiling a book such as this is almost beyond comprehension. A glance at the great number of references cited and digested, the subject and author index which add greatly to the value of the work, give an idea of the tremendous task. These together with the expert knowledge exhibited in presenting the material and the very evident careful planning which must have been done in advance, have produced a work which is invaluable to future research in catalysis.

R. H. OPPERMANN.

THE RING INDEX, A LIST OF RING SYSTEMS USED IN ORGANIC CHEMISTRY, by Austin M. Patterson and Leonard T. Capell. 661 pages, 16 × 24 cms. New York, Reinhold Publishing Corporation, 1940. Price $8.00.

This work actually had its beginning in the year 1921 when there was reported to the Board of Editors of the Journal of the American Chemical Society that data upon organic ring systems and their systematic numbering had been accumulated in connection with the indexing of Chemical Abstracts. The report asked at the time whether it would be advisable to publish a catalog of such systems in the JOURNAL or elsewhere. The Board decided it would be, but felt it extremely desirable to secure first an agreement among chemists as to the numbering. Subsequently the numbering system was drawn up, submitted to various world wide chemical societies and individuals and adopted for use and applied here.

The ring index is the result of many years work. It is interesting to note the number of known ring systems has increased from an estimated 800 in 1922 to over 4000 at the present time. This book is a catalog of them. The collection attempts to be complete through the literature of 1938 with some new systems reported in 1939. There is a name index, the use of which enables the user to locate the system knowing its name only. Otherwise the number and size of the rings composing the system must be determined. Each system has a serial number which may be used for identification and for each system there is at least one literature reference noted.

The collection includes (1) simple parent rings and (2) parent systems of more than one ring in which the rings are united by having one or more atoms in common. It thus comprises simple and "fused," or anellated, systems (including spyro forms), but not systems like biphenal or triphenalmethane, in which the rings are united only by valences or by atoms not belonging to the rings.

Very complete instructions for use are given as well as explanations of details of arrangement and content. An appendix contains a reprint from the Journal of the American Chemical Society on the international rules for numbering ring systems. The work is well done in every respect. It is an invaluable reference tool.

R. H. OPPERMANN.

SCIENCE ON PARADE, by A. Frederick Collins. 314 pages, illustrations, 15 × 21 cms. New York, D. Appleton-Century Company, 1940. Price $3.00.

As the title implies, this book contains a story of present day scientific achievements. Many of them will be recognized by readers as those exhibited at the recent New York World's Fair and there are others which could not well be transported to the exhibition grounds. The story is an admirable translation of the scientific and technical to the everyday language in describing the parts, functions and products of practical modern machines which operate for the benefit of mankind. The author has had considerable experience in writing this type of literature and his scientific background gives much weight to the work.

The book is divided into eleven parts, each devoted to a specific subject. It starts out with Astronomy on Parade relating briefly the story of the telescope, leading up to a description of the 200 inch telescope, its various parts and their functions, and finally to an account of what is expected from the use of it. Aviation is so large a subject now and the space required to cover it adequately would be prohibitive that apparently the author has chosen the theme of the super-clipper as the outstanding example in aviation which would envelope the largest section of the subject. The construction and operation of these ships are explained down to a small detail, including the gyropilot, the physics of the medium above the earth's surface through which the ships travel, and the routes and weather. Other subjects, just as diverse as the two mentioned above, are given attention. Synthetic compounds are discussed under the heading of Chemistry on Parade, man made lightning under electricity, the sterilamp under health, cool-light lamps under light, the electronic piano under music, photography, radio, synthetic speech, and television. There are many drawings, diagrams and illustrations assisting the descriptive matter in the book and there is a subject index in the back.

The book belongs to that class of literature which has for its purpose the raising of the general knowledge of the layman about scientific achievements which are in practical operation. It is a revelation of the value of pure research, as well as the results of combinations of knowledge in many different lines. The layman can most certainly gain by reading the book from cover to cover.

R. H. OPPERMANN.

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